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AUTHORITY

AFMC, 26 Aug 1997

PL-TR--94-1138

PL-TR--
94-1138

10 K CRYOCOOLER DEVELOPMENT PROGRAM

Lockheed Missiles & Space Company, Inc.
Palo Alto, CA

August 1994

Final Report

PHILLIPS LABORATORY
Space and Missiles Technology Directorate
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

19951204 053

PL-TR--94-1138

This final report was prepared by Lockheed Missiles & Space Company, Inc., Palo Alto, CA, under contract F29601-92-C-0110, Job Order 110102AF. The Laboratory Project Officer-in-Charge was Brian Whitney (VTPT).

This technical report has been reviewed and is approved for publication.

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Project Officer

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Chief, Space Power and
Thermal Management Division

HENRY L. PUGH, JR., Col, USAF
Director of Space and Missiles Technology

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DRAFT SF 298

1. Report Date (dd-mm-yy) August 1994	2. Report Type Final	3. Dates covered (from... to) 9/92 to 8/94
4. Title & subtitle 10 K Cryocooler Development Program		5a. Contract or Grant # F29601-92-C-0110
		5b. Program Element # 62601F
6. Author(s)		5c. Project # 1101
		5d. Task # 02
		5e. Work Unit # AF
7. Performing Organization Name & Address Lockheed Missiles & Space Company, Inc. Palo Alto, CA		8. Performing Organization Report #
9. Sponsoring/Monitoring Agency Name & Address Phillips Laboratory 3550 Aberdeen Ave SE Albuquerque, NM 87117-5776		10. Monitor Acronym
		11. Monitor Report # PL-TR-94-1138

12. Distribution/Availability Statement Distribution authorized to U.S. Government agencies and their contractors only; Critical Technology; August 1994. Other requests for this document shall be referred to AFMC/STI.

13. Supplementary Notes This report is published in the interest of STINFO exchange. The established procedures for editing reports were not followed for this technical report.

14. Abstract This program was broken into three separate phases. The objective of Phase I was to identify cooling methods and critical components necessary for the development of a continuous 10 Kelvin cryocooler. This phase was to contain several contractors, each with their own conceptual design. The objective of Phase II was to characterize and evaluate these components. This would essentially be a proof-of-principal phase that would give an initial GO/NO-GO decision point for any of the contractors in Phase 2. The objective of Phase 3 was to downselect to the most promising technology and bring that program through building an engineering design model (EDM) and evaluating the performance of that EDM at Phillips Laboratory.

15. Subject Terms Cryocooler, cold head,

Security Classification of			19. Limitation of Abstract	20. # of Pages	21. Responsible Person (Name and Telephone #)
16. Report Unclassified	17. Abstract Unclassified	18. This Page Unclassified	Limited	164	Brian Whitney (505) 846-1867

PROJECT TITLE: 10 K CRYOCOOLER DEVELOPMENT

PROJECT MANAGER: Brian M. Whitney

CONTRACTOR: Lockheed - 3 Stage Stirling Cryocooler

CONTRACT NUMBER: F29601-92-C-0110

DESCRIPTION: Cryocooler designs with minimal weight, high efficiency and reliability are sought by this program. This project will develop the technology to provide continuous cooling at 10 K. Cryocoolers at this temperature range are enabling technology for future satellites the use VLWIR focal plane arrays or low temperature superconducting devices. Such low temperatures are required for IR sensor cooling to increase the signal-to-noise ratio.

OBJECTIVES: This program was broken into three separate phases. The objective of Phase 1 was to identify cooling methods and critical components necessary for the development of a continuous 10 Kelvin cryocooler. This Phase was to contain several contractors, each with their own conceptual design. The objective of Phase 2 was to design, develop and fabricate the critical components of the cryocooler and then to characterize and evaluate these components. This would essentially be a "proof-of-principle" phase that would give an initial GO/NO-GO decision point for any of the contractors in Phase 2. The objective of Phase 3 was to downselect to the most promising technology and bring that program through building an engineering design model (EDM) and evaluating the performance of that EDM at Phillips laboratory.

TECHNICAL DEFICIENCIES: Thermodynamic efficiency decreases as temperature decreases (i.e. it takes increasing amounts of power to cool to lower and lower temperatures). To reach temperatures as low as 10 Kelvin the thermodynamic efficiency drops to a few percent of what is theoretically possible. Much of this is due to losses in the system, such as regenerator (heat exchanger) losses in the cold end. Regenerator materials naturally lose heat capacity and thermal conductivity below approximately 20 Kelvin, thus making cooling to these temperatures increasingly difficult. The 10 K Cryocooler program is designed to advance technology to make these systems more efficient.

TECHNICAL APPROACH: Begin with system engineering to define cryocooler design/performance requirements of future space systems at 10 K. Begin development of critical components which need advancement beyond state-of-the-art to reach these requirements. These components will be fabricated and tested to demonstrate the improvement in cryocooler performance they would enable. This demonstration will allow selection of the most promising approach for the engineering model. Design, fabricate and test an engineering development model (EDM) cryocooler to demonstrate continuous 10 K cooling.

SYSTEM REQUIREMENTS:

Cooling	0.15 W @ 10 K
	2.0 W @ 35 K
	5.0 W @ 80 K
Input power	< 1000 W
Weight	< 100 kg
Total satellite penalty	< 250 kg
Operational life	10 years

Reliability	> .95
Vibration	< .05 N

USER NEED / PRIORITY: Supports LWIR, VLWIR requirements

COST / PERFORMANCE PAYOFF: Enabling technology for future satellites that use VLWIR focal plane arrays or low temperature superconducting devices.

KEY MILESTONES:
Oct 92 : Begin Phase 1 (3 contractors)
Mar 93 : Downselect to one contractor (Aerojet Corp)
Mar 93 : Lockheed contract canceled

SUMMARY:

This contract was let in Oct 1992 as part of a three pronged effort to pursue cryogenic cooling at 10 Kelvin. TRW, Lockheed, and Aerojet were contracted to perform preliminary component designs, trade studies, critical component identification and Phase 2 test plan under Phase 1 of this program. Lockheed proposed a three stage Stirling cryocooler to satisfy the requirements of this program .

This effort by lockheed proved to be unsatisfactory at the end of Phase 1 due to the inability to meet all of the specified requirements. Although Lockheed's design theoretically could have met the cooling requirements it used more than the allotted 1000 W of input power and more than the allotted 350 kg of total spacecraft penalty weight. Because of the requirements issue, Lockheed was not chosen to continue into Phase 2 of the 10 K program and the program was canceled.

Lockheed

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CONCEPT REVIEW
10K CRYOCOOLER
DEVELOPMENT CONTRACT

Air Force
Phillips Laboratories
10K CoDR

TO Air Force Phillips Laboratory
Brian Whitney, Technical Monitor

FROM Lockheed Research Laboratory
Palo Alto, California
Ted Nast, Program Manager

AT Lockheed/Palo Alto

March 4, 1993

AGENDA

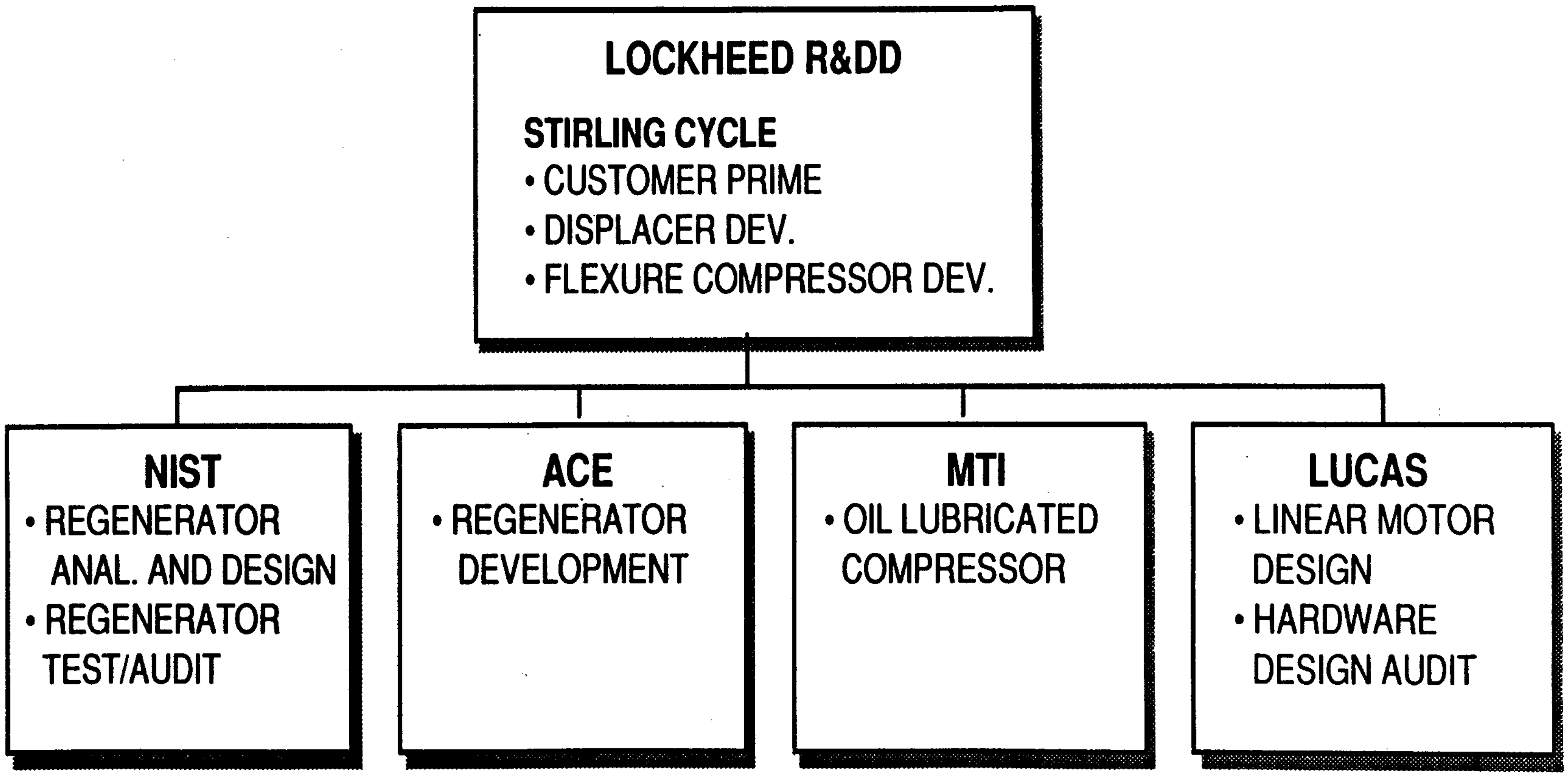
AGENDA FOR 10K CRYOCOOLER DEVELOPMENT PROGRAM
CONCEPT REVIEW, LOCKHEED PALO ALTO RESEARCH LABORATORY
MARCH 4, 1993

9AM-9:30	LOCKHEED CRYOCOOLER TECHNOLOGY OVERVIEW	Nast
	contracts/capabilities	
9:30-10:00	PHASE 1 OVERVIEW	Nast
	technical summary	
	phase 2 plans	
10:00-10:15	BREAK	
10:15-12:00	10K TECHNICAL RESULTS	
	layout	Isaac
	displacer design	Isaac
	cooling performance predictions	Yuan
	NIST cooling analysis	Nast
	ACE regenerator	Nast
	MTI compressor design	Champagne
	flexure compressordesign	Champagne
12:00-1:00	LUNCH	
1:00-1:30	LAB TOUR	
1:30-2:00	TECHNICAL RESULTS (CONTD.)	
	alignment work	Naes
	critical technologies demo/plans	Nast
2:00-2:15	SUMMARY	Nast

LOCKHEED CRYOCOOLER TECHNOLOGY OVERVIEW

PHASE ONE OVERVIEW

TEAMING ARRANGEMENT STRUCTURE



RECENT ENABLING TECHNOLOGY ADVANCEMENTS

TECHNOLOGY ITEM	ADVANCE	COMMENTS
Flexure bearing support of moving masses	Extensive development and test demonstration over the last 10 years,	Allows clearance gap to be used with relatively simple hardware, replaces gas bearings and magnetic bearings
Regenerator materials	New materials with high specific heats (rare earth compounds) being demonstrated, large improvement in performance below about 30K	Japanese group attained 2.2K with Gifford McMahon operating with rare earth compounds, manufacturing problem and weight loss with time still issues.
Induced vibration	Demonstration of millipound levels with back to back linear motors demonstrated at LMSC	Scaling to sizes for 10K cryocooler indicates requirements are attainable
Clearance gap control	Extensive development because of many machines utilizing flexures, several groups working problem.	Attainable, repeatable gaps approximately one half of prior values, 0.25 mil gaps attainable on compressor piston by LMSC-Lucas. Extensive LMSC development in dynamic modeling and dynamic measurements. Excellent tools and understanding.

Lockheed

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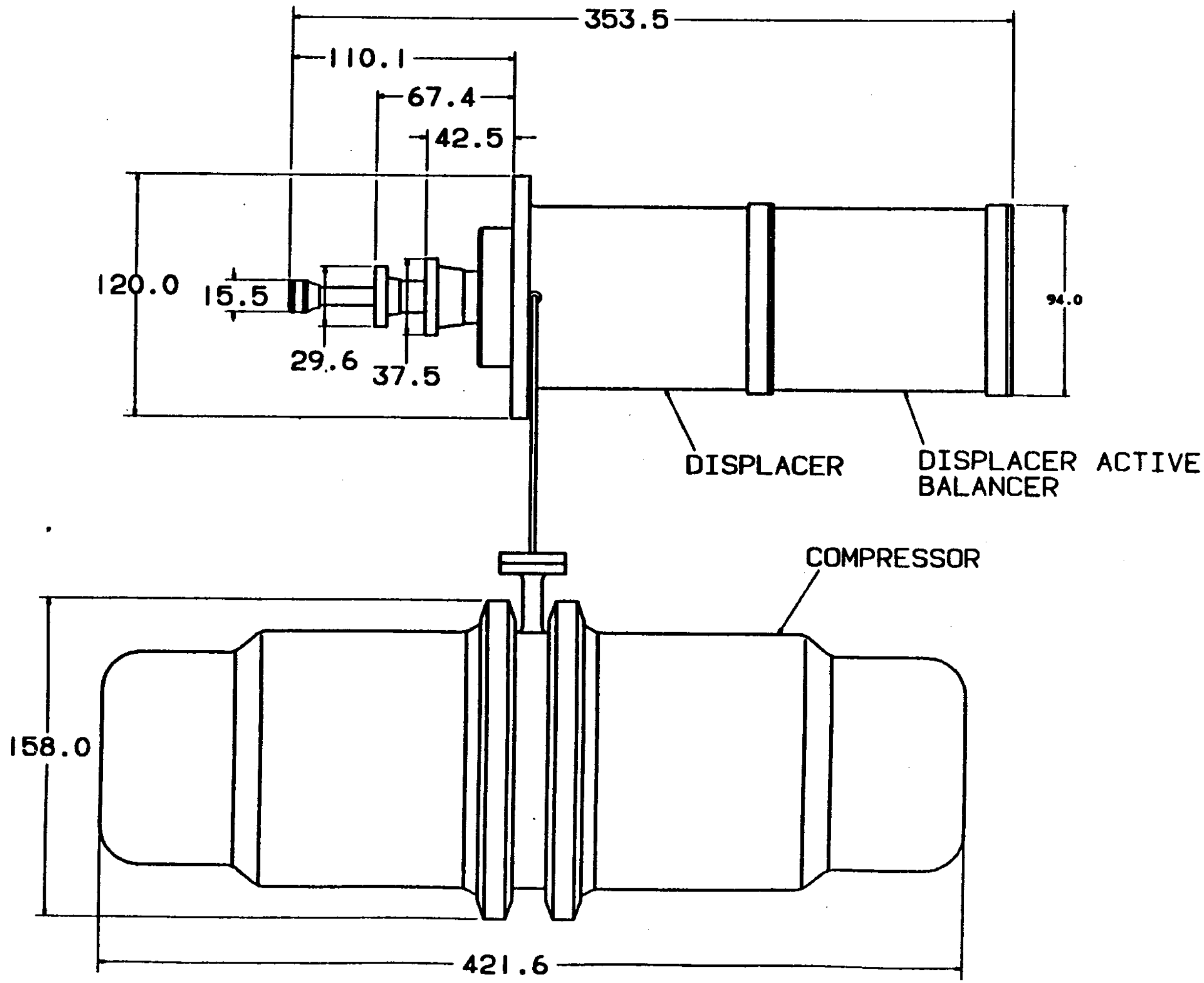
3 STAGE CRYOCOOLER SYSTEM IS MADE UP OF MODULAR COMPONENTS

Air Force
Phillips Laboratories
10K CoDR



DIMENSIONS IN MM

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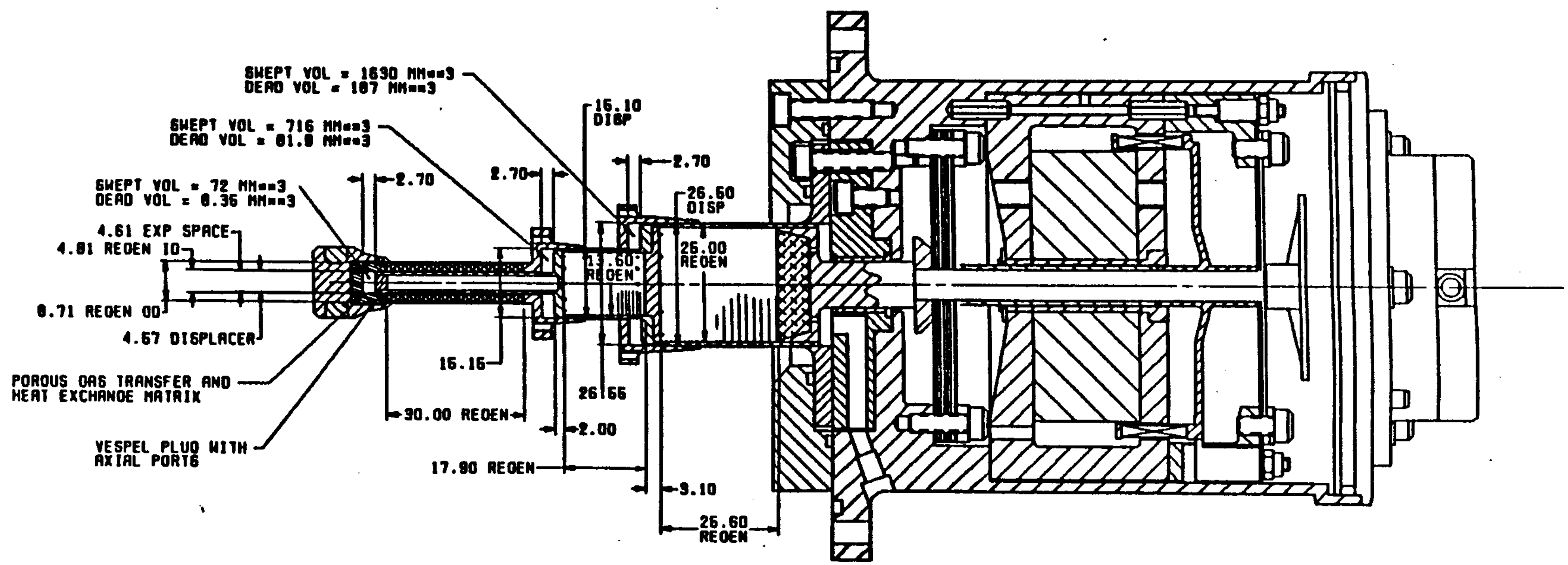
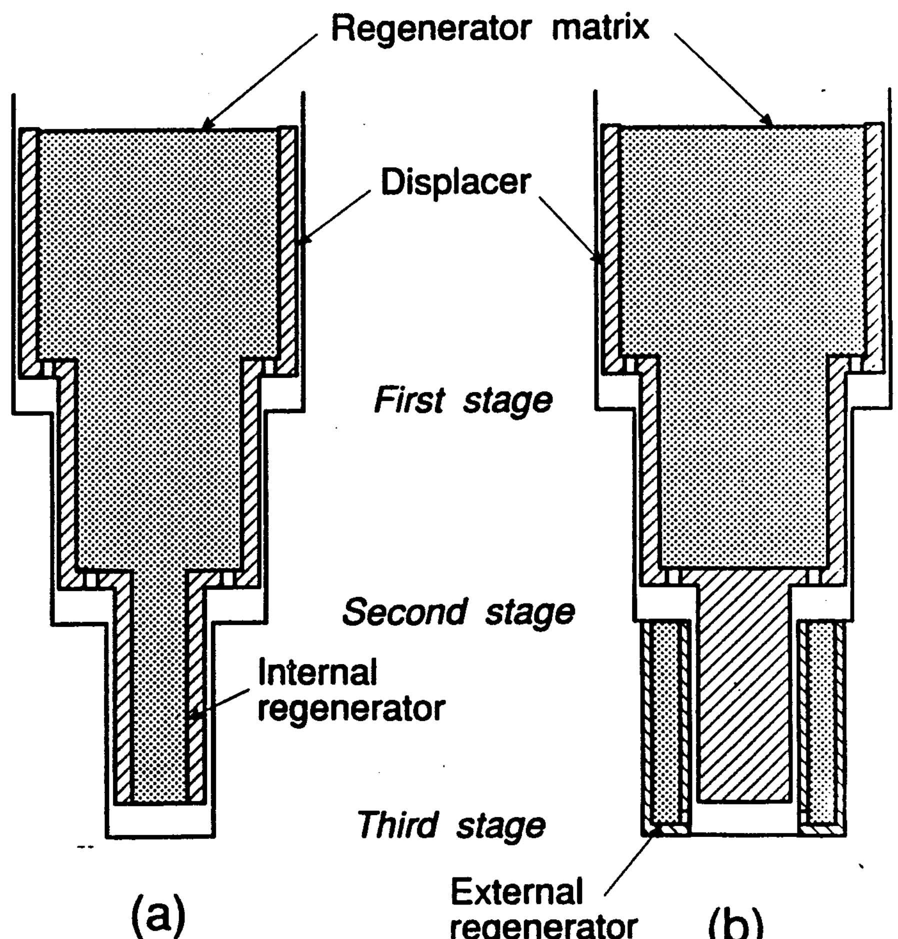
3 STAGE CRYOCOOLER SYSTEM IS MADE UP OF MODULAR COMPONENTS

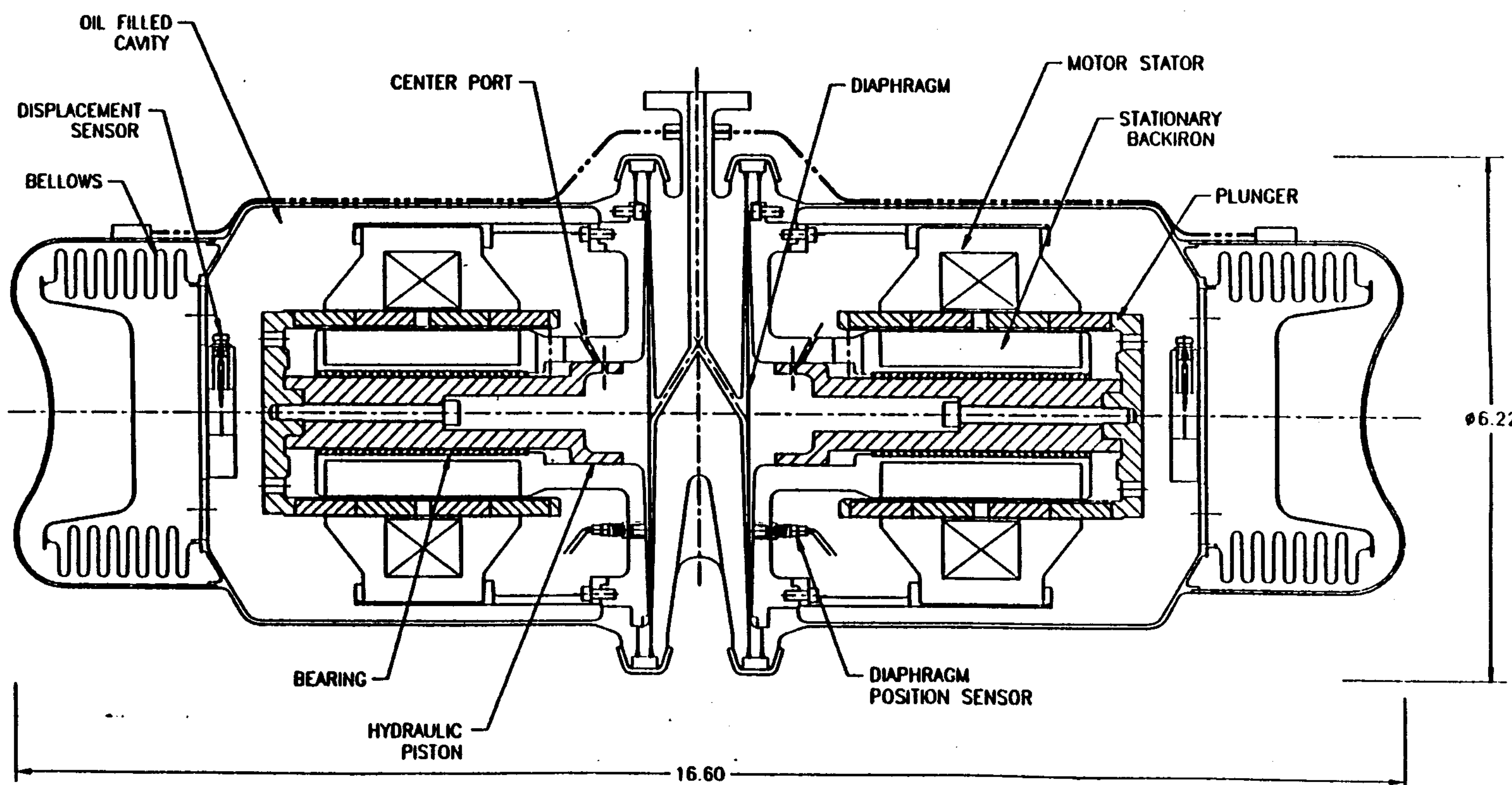
Air Force
Phillips Laboratories
10 K CoDR



REGENERATOR ARRANGEMENTS SHOWING FIXED AND MOVING 3RD STAGE



16-mm STROKE, 40 Hz, 23.8 cc



CONCURRENCE OF REQUIREMENTS BASED ON MODELING AND TESTING

REQUIREMENTS	PROPOSED VALUES	BASIS
Cooling loads, • 1st stage, 5W @ 80K + -2K • 2nd stage, 2W @ 35K + -1K • 3rd stage, 0.15W @ 10K + -0.1K	5W @ 80K 2W @ 35 0.15W @ 10	Two separate prediction models indicate cooling loads will be met at all three stages
Power Supply 28VDC + -20%	28VDC	Consistent with present electronic controller development
Maximum vibration 0.05 Newtons	≤ 0.05 Newtons	Based on laboratory measurements on similar systems scaled to larger size proposed
Maximum cryocooler Weight 100Kg	Compressor: 14.9 Kg Displacer: 4.3 Kg Displacer Balancer: 2.0 Kg Electronic Controller: 10.0 Kg Misc.: 2.0 Kg Total: 33.2 Kg	Actual hardware weight plus detail weight analysis of compressor and preliminary estimate for controller
Total Vehicle Effective Weight (goal), 250Kg. (1) Maximum input power, 1000W	165 Kg 528 W (including controller)	Based on predicted weight plus 0.25 Kg per W power Thermodynamic analysis on two programs
Operating Life, 2 years ground plus 10 years on orbit	2 Yrs. ground plus 10 years on orbit	Based on an extrapolation of extensive analysis and test data on smaller systems

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SRPM RUN SUMMARY

Air Force
Phillips Laboratories
10K CoDR

Net Ref. Power (W)	0.145, 2.0, 5.0
Displacer Stroke (mm)	7
Disp. Swept Volumes (cc)	0.137, 1.12, 5.7
Clearance Gaps (Microns)	17, 20, 30
Comp. Swept Vol. (cc)	28.86
Compressor P-V (W)	349
Operating Frequency (Hz)	40
Fill Pressure (Psia)	220

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SUMMARY OF DISPLACER LOSS TERMS FOR A TYPICAL RUN

Air Force
Phillips Laboratories
10K CoDR

	80K FIRST STAGE	35K SECOND STAGE	10K THIRD STAGE
Gross Cooling	35.2 W	6.5 W	0.64 W
Regenerator Loss	22.45 W	3.6 W	0.31 W
Blow-By Loss	7.75 W	0.9 W	0.185 W
Net Cooling	5 W	2.0 W	^0.15 W

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CONCLUSIONS FROM NIST

Air Force
Phillips Laboratories
10K CoDR

THREE STAGE STIRLING CAN EASILY MEET SPECIFICATIONS

40 HZ OPERATION PREFERRED BECAUSE OF SMALLER COMPRESSOR

427 W INPUT POWER WITH LARGE EXCESS COOLING POWER

387 W INPUT TO MEET REQUIREMENTS

20 MICRON CLEARANCE GAP FOR 3RD. STAGE

LOW POROSITY REGENERATORS NECESSARY FOR HIGH EFFICIENCY

Regenerator Design
Porosity and D_h Trades
Cooling Power

Hydraulic Diameter (microns)	Net Cooling Power (Watts)				
	Porosity				
	0.10	0.15	0.20	0.25	0.40
10.0			no solution	0.91	0.71
14.1			0.91	0.85	0.63
20.0			0.78	0.72	0.51
28.3		no solution	0.59	0.50	
40.0	no solution	0.40	0.28		0.10

- **Use REGEN 3.1 for calculations**
  - **perforated plate system is modelled as axial tube flow**
  - **the matrix volume of the perforated plate system is equal to the packed sphere case**

- **Baseline case**
  - **100 micron Er_3Ni spheres with porosity = 38%**
  - **cooling power = 0.61 Watts**

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BASELINE WEIGHT SUMMARY

Air Force
Phillips Laboratories
10K CoDR

	KG	LBS.	
MTI COMPRESSOR	14.89	32.7	
DISPLACER	4.3	9.46	
DISPLACER BALANCER	2.0	4.4	
ELECTRONIC CONTROLLER	10.0	22.0	
CABLES AND SUPPORT HDW.	2.0	4.4	
	-----------	-----------	REQUIREMENTS
TOTALS	33.2KG	73LBS	100KG MAX.
TOTAL POWER INPUT	528 WATTS		1000W MAX.
EFFECTIVE POWER WEIGHT(1)	132 KG		
TOTAL VEHICLE EFFECTIVE WT.	165KG		250KG GOAL

(1) BASED ON 0.25KG/W

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POWER BUDGET SUMMARY

Air Force
Phillips Laboratories
10K CoDR

	POWER, WATTS	
MTI COMPRESSOR	422	
DISPLACER	4	
DISPLACER BALANCER	1	
ELECTRONICS TURN ON POWER	12	
ELECTRONICS INEFFECIENCY	89	REQUIREMENT
TOTAL POWER INPUT	528 WATTS	1000 W MAX.

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10 K CRYO COOLER FLIGHT ELECTRONICS CARDS

- MOST OF THE CIRCUIT CARDS FROM THE LOCKHEED IN-HOUSE FLIGHT ELECTRONICS DESIGN CAN BE USED WITH THIS LARGER COOLER WITH LITTLE OR NO CHANGE.
  - INTERFACE COMPUTER DOES NOT CHANGE
  - SENSOR SIGNAL CONDITIONING DOES NOT CHANGE
  - ANALOG CONTROL LOOPS DO NOT CHANGE EXCEPT FOR SOME COMPONENT VALUES
  - DISPLACER DRIVE LINEAR AMPLIFIER NEEDS SLIGHTLY INCREASED CAPACITY TO DRIVE THE LARGER DISPLACER LOAD
  - SECONDARY POWER SUPPLY NEEDS SLIGHTLY INCREASED CAPACITY TO DRIVE THE LARGER DISPLACER LOAD

- ONLY THE COMPRESSOR DRIVE CARD NEEDS TO BE SIGNIFICANTLY REDESIGNED
  - THREE CARDS INSTEAD OF TWO ARE REQUIRED TO DRIVE THE TWO LARGER COMPRESSOR MOTORS

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10 K CRYO COOLER FLIGHT ELECTRONICS ENCLOSURE

- IF CURRENT RIPPLE CAN BE TOLERATED ON THE 28 VDC POWER BUS, THE ENCLOSURE MUST ONLY GROW ENOUGH TO HOUSE THE ADDITIONAL COMPRESSOR DRIVE CARD AND SOME NEW CONNECTORS
  - VOLUME WILL INCREASE FROM ABOUT 470 CUBIC INCHES TO ABOUT 550 CUBIC INCHES
  - MASS WILL INCREASE FROM ABOUT 6.2 KG TO ABOUT 7 KG
- IF MIL STD 461 OR EQUIVALENT CONDUCTED EMISSIONS REQUIREMENTS MUST BE MET, THE ENCLOSURE WILL NEED TO HOUSE A LOT MORE ELECTRICAL ENERGY STORAGE CAPABILITY
  - VOLUME WILL INCREASE ANOTHER 50% TO ABOUT 830 CUBIC INCHES
  - MASS WILL INCREASE ANOTHER 50% TO ABOUT 11 KG

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RELATIVE POWER CONSUMPTION FOR VARIOUS STAGES

Air Force
Phillips Laboratories
10K CoDR

STAGE/REQMTS.	PV WORK FOR STAGE
1st stage, 80 K, 5W	157 W
2nd stage, 35K, 2W	91 W
3rd stage, 10K, 0.15 W	61W

Results Show first stage dominates the power requirements

CRITICAL COMPONENTS ASSESSMENT AND RESOLUTION

NO.	ITEM	RISK	RESOLUTION	COMMENTS
1	displacer thermodynamic performance	cooling capacity below specifications,	early build and test of displacer. early validation with time for rework	phase 2 testing performed for cooling capability and temperature, use laboratory and commercial compressor
2	regenerator thermal performance	cooling below specification	thermal loss and pressure drop tests on several candidates	phase 2 testing to be performed on NIST apparatus on several regenerators.
3	regenerator life capability	shifting, clumping, pulverizing etc. will change performance over lifetime	avoid use of unsupported configurations such as spheres	requires life testing on cryocooler
4	displacer clearance gap control	wear (if gaps too small or dynamics problem) or large thermal losses (if gaps too large)	validate design, manufacture and assembly on structural model	build and test displacer structural model (with regenerator ballasted) early in phase 2.
5	induced vibration	large forces resulting from large moving massses	analysis supported by scaling from existing units	displacer vibration output measured in phase 2, compressor in phase 3
6	scaling of flexure supports for larger masses	minimal risk, detailed analysis performed	additional modeling in phase 2, build and test springs	phase 2 testing. Flexures sent to PHILLIPS for evaluation
7	MTI compressor, life limiting elements	long term stability of diaphragm and plunger sensors, compressor/control instabilities, higher order vibration harmonics	system tests	in house life testing on system at MTI. Performance testing under AFPL contract.
8	internal outgassing of organics	freezing of condensibles, reduced thermal performance	modeling utilizing existing codes, design of coil/potting for fast bakeout	calculation of outgassing rates in phase 2
9	management of waste heat	high temperatures degrade thermal performance.	modeling utilizing existing codes. Verify of displacer test.	critical for flexure compressor demonstrate manufacturing during phase2

PHASE 2 PRINCIPAL TEST ACTIVITIES

BUILD AND TEST A STRUCTURAL MODEL OF DISPLACER TO DEMONSTRATE ALIGNMENT, DYNAMICS AND MANUFACTURING

BUILD AND TEST A THERMAL DISPLACER TEST BED TO VERIFY ADEQUATE COOLING AND OPTIMIZE PARAMETERS

THE ABOVE UNITS WOULD UTILIZE AN EXISTING COMPRESSOR MOTOR/HOUSING AS THE DISPLACER DRIVE

LMSC WOULD BUILD A BRASSBOARD FLEXURE COMPRESSOR ON COMPANY FUNDING FOR DISPLACER TESTS

additional testing would include regenerator testing (at NIST), large flexures, low outgassing coils, and displacer induced vibration

10K TECHNICAL RESULTS

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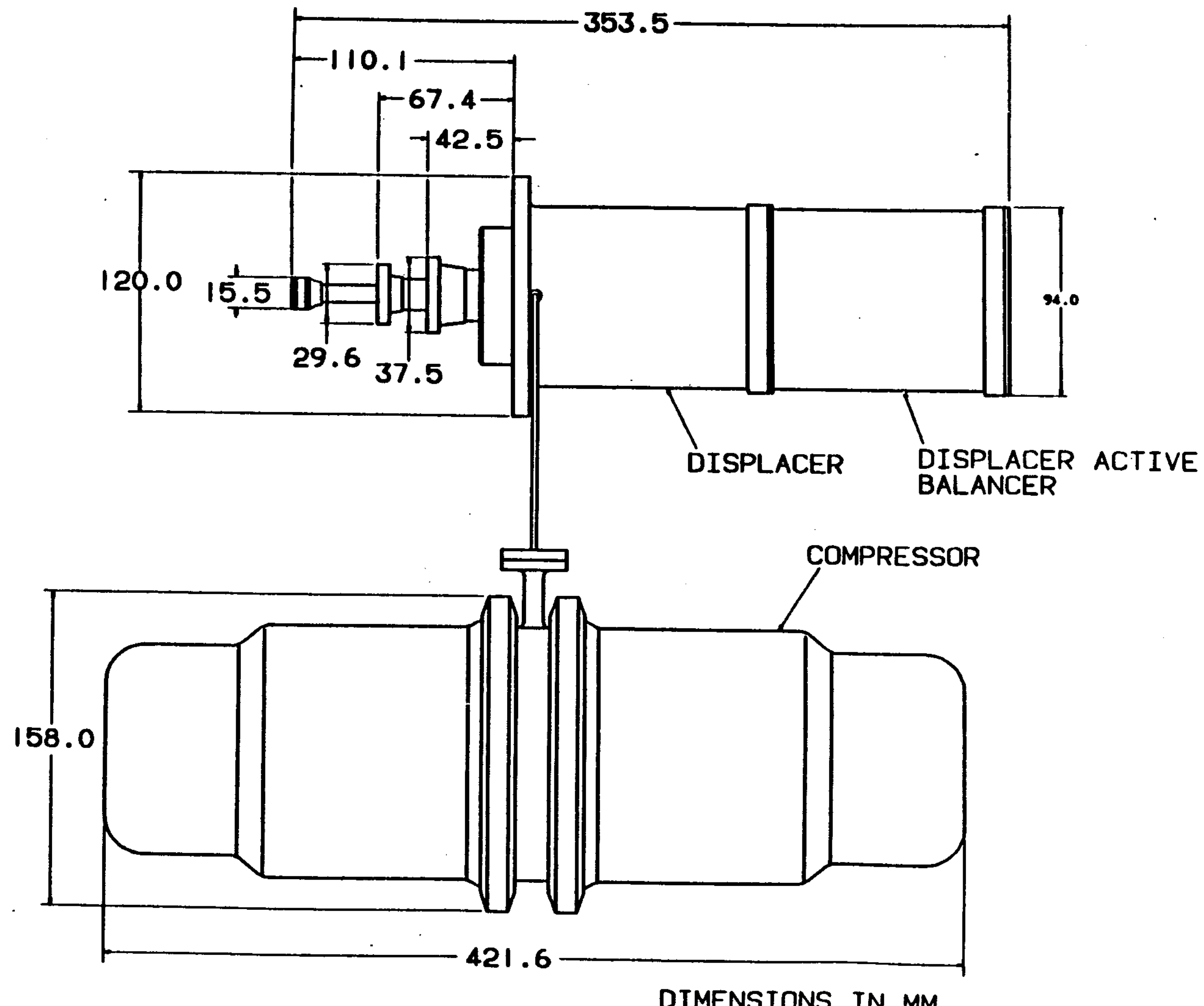
3 STAGE CRYOCOOLER SYSTEM IS MADE UP OF MODULAR COMPONENTS

Air Force
Phillips Laboratories
10K CoDR



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BASELINE WEIGHT SUMMARY

Air Force Phillips Laboratories 10K CoDR

	KG	LBS.	REQUIREMENTS
MTI COMPRESSOR	14.89	32.7	
DISPLACER	4.3	9.46	
DISPLACER BALANCER	2.0	4.4	
ELECTRONIC CONTROLLER	10.0	22.0	
CABLES AND SUPPORT HDW.	2.0	4.4	
TOTALS	33.2KG	73LBS	100KG MAX.
TOTAL POWER INPUT	528 WATTS		1000W MAX.
EFFECTIVE POWER WEIGHT(1)	132 KG		
TOTAL VEHICLE EFFECTIVE WT.	165KG		250KG GOAL

(1) BASED ON 0.25KG/W

POWER BUDGET SUMMARY

	POWER, WATTS	
MTI COMPRESSOR	422	
DISPLACER	4	
DISPLACER BALANCER	1	
ELECTRONICS TURN ON POWER	12	
ELECTRONICS INEFFECIENCY	89	REQUIREMENT
TOTAL POWER INPUT	528 WATTS	1000 W MAX.

DISPLACER FEATURES

* COMPRESSOR LINEAR MOTOR
* STATIONARY 3RD STAGE REGENERATOR
* JACKETED TRANSFER LINE
* ISOTHERMALIZER AT COLDFINGER BASE
* GAS DIFFUSER IN DISPLACER WARM END
* ANNULAR GAS TRANSFER AT EACH COLD STAGE
* THERMAL MASS AT COLD END
* EASILY REMOVED COLDFINGER
* STANDARD COMPRESSOR BASED BALANCER

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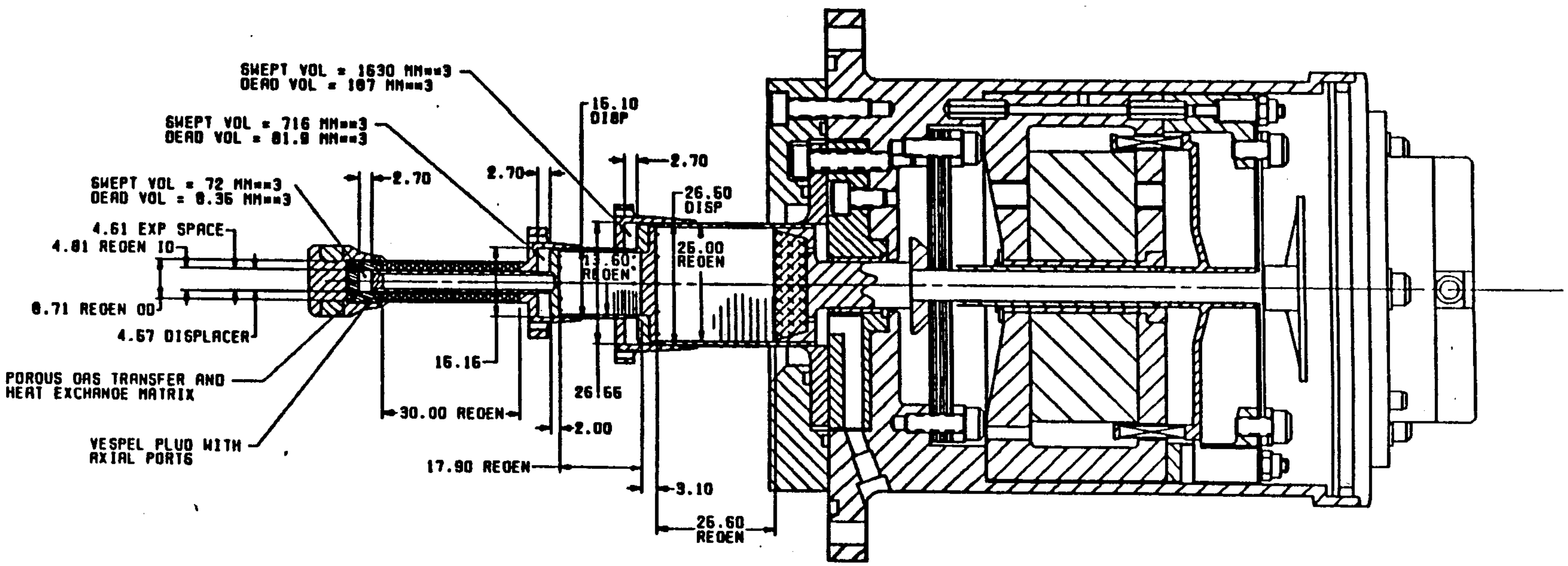
THE 10K DISPLACER IS BASED ON THE CCS1000 COMPRESSOR MOTOR

Air Force
Phillips Laboratories
10 K CoDR

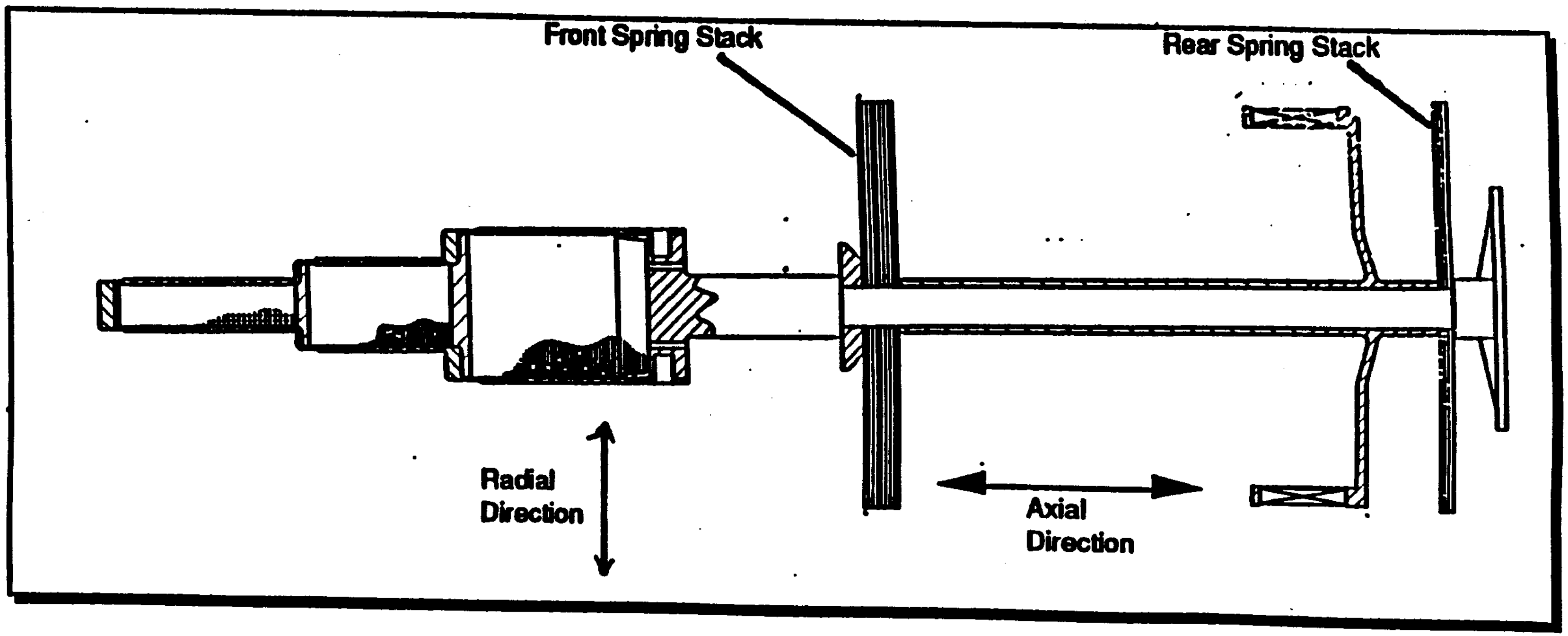


ADVANTAGE OF COMPRESSOR MOTOR FOR 10K DISPLACER

<u>The current LMSC compressor is a good match for the displacer.</u>

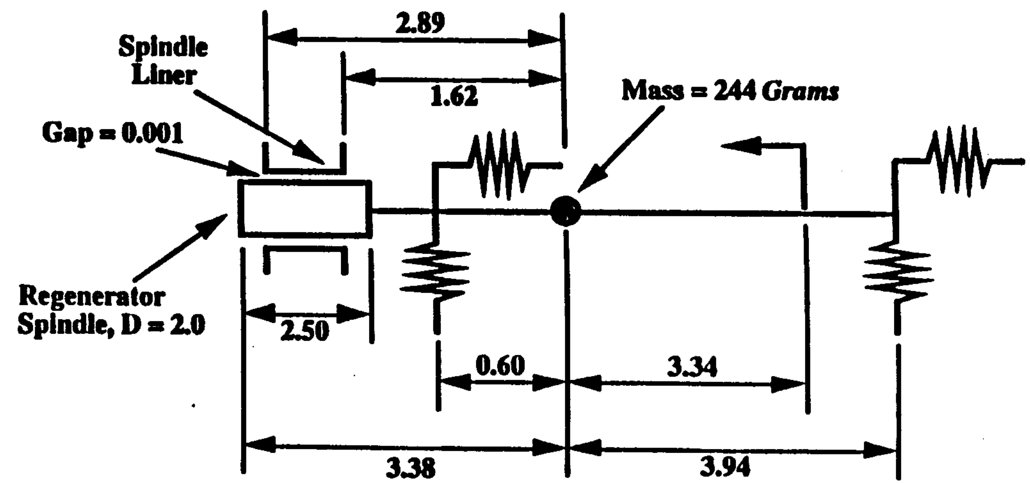
* **It satisfies all requirements for driving the large regenerator.**
* **Suspension spring stresses are low.**
* **It behaves well dynamically when mated with the regenerator.**
* **The overall weight is compatible with the system.**
* **An active balancer is available.**
* **Controller interfaces are in place and well understood.**
* **Hardware is existing and readily available.**

MOVING MASS IS SUPORTED BY 2 STACKS WITH UNEQUAL NUMBERS OF IDENTICAL SPRINGS



10K DISPLACER SPRING CONFIGURATION STUDY

- **10K Displacer dynamics model (*Dimensions in Centimeters*):**



- **LMSC (0.125,420°) spiral spring, 0.012 *in.* thickness, 301 stainless steel used**

- **NOTE: Model neglects force and moment caused by flow past regenerator...**
  -- small end-to-end pressure gradient; no destabilizing flow effects

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10K DISPLACER SPRING PACK STUDY MATRIX

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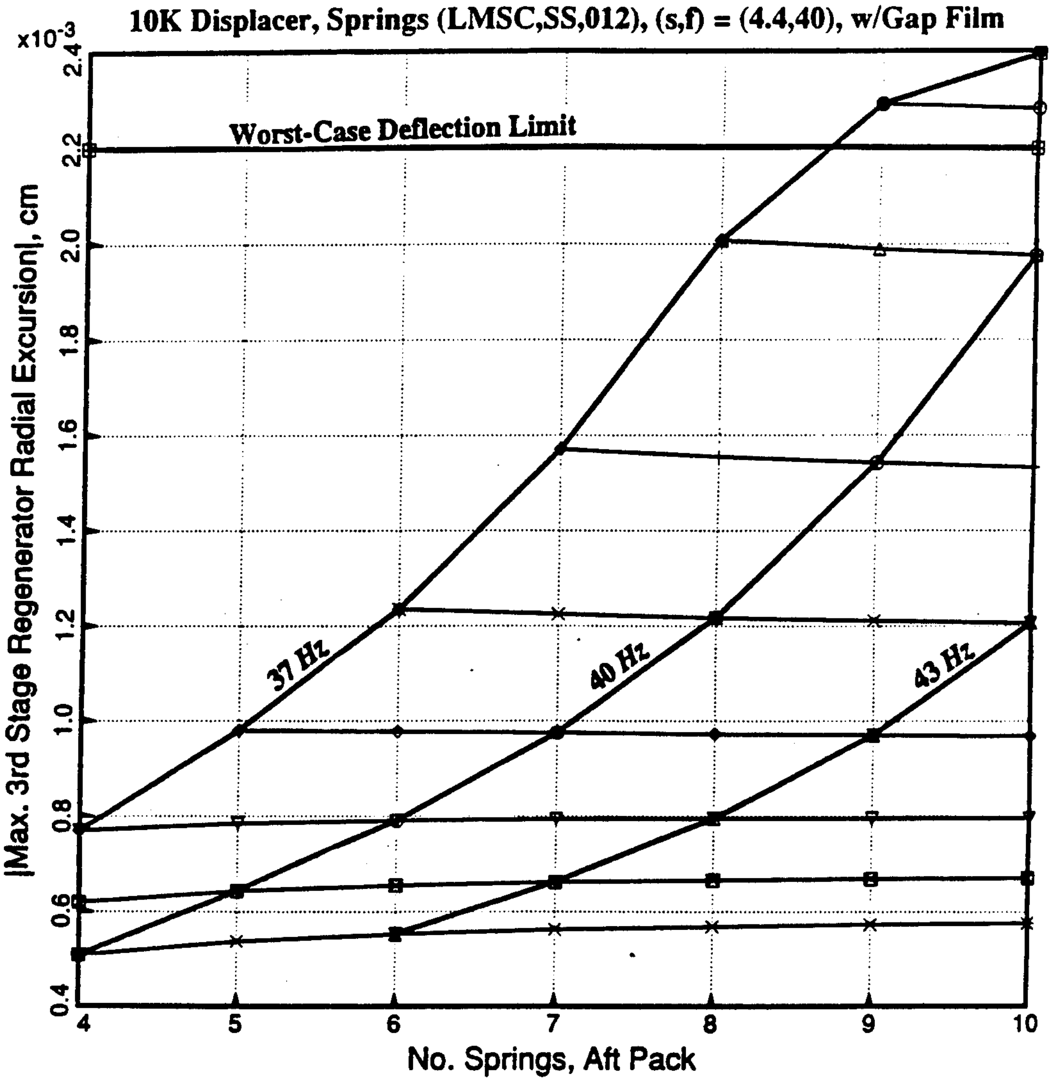
10K Displacer
Suspension Configuration Study
Results Summary

LEGEND
- □ 4 Springs, Forward Pack
- ○ 5 Springs, Forward Pack
- △ 6 Springs, Forward Pack
- + 7 Springs, Forward Pack
- × 8 Springs, Forward Pack
- ◇ 9 Springs, Forward Pack
- ▽ 10 Springs, Forward Pack
- ⊠ 11 Springs, Forward Pack
- ✳ 12 Springs, Forward Pack



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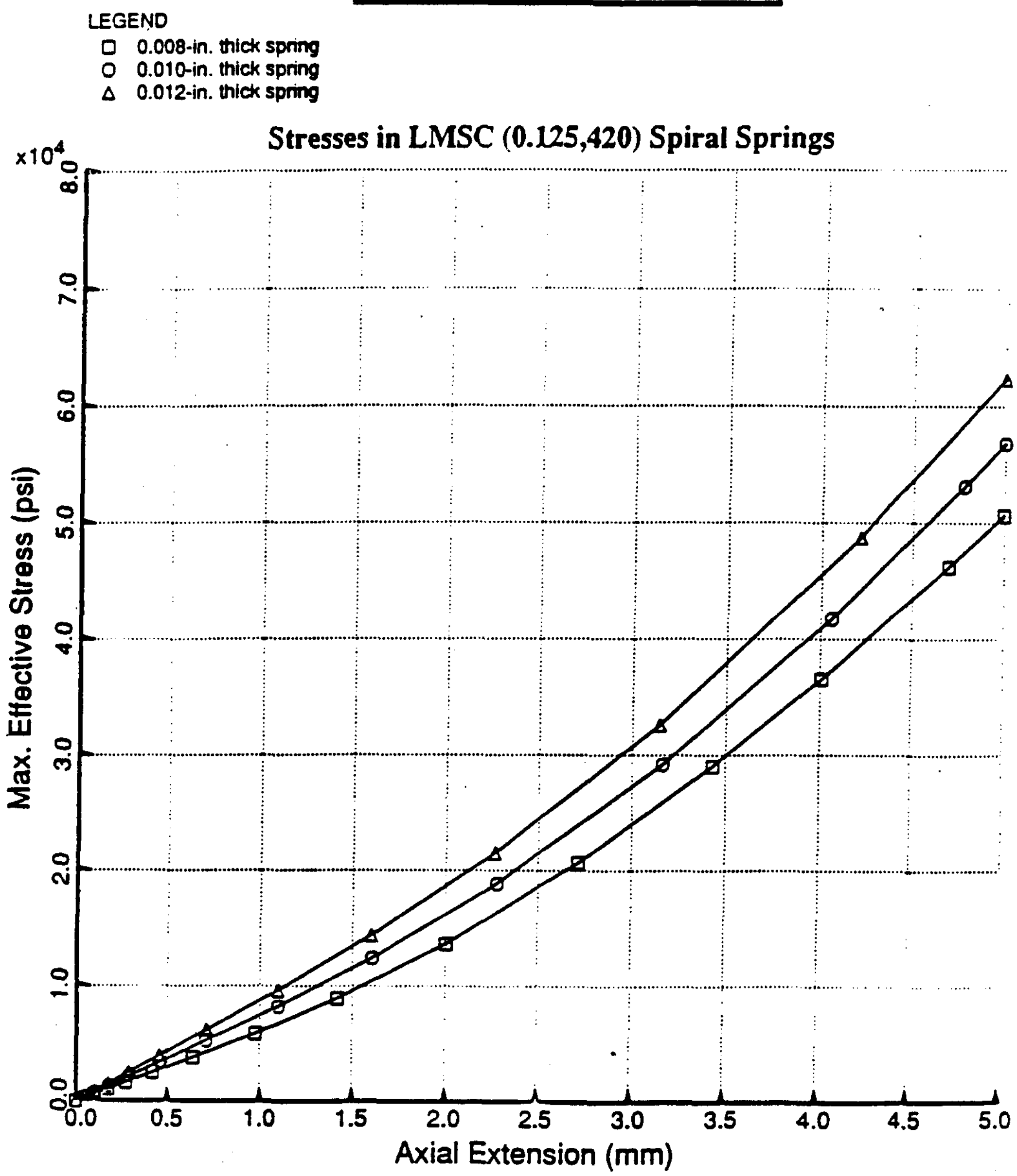
STRESSES IN DISPLACER SPRINGS

Convergence Study: 1X Model

Effective Stress @ thin section



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10K DISPLACER SPRING
SUMMARY

* The current LMSC compressor spring is an ideal choice.

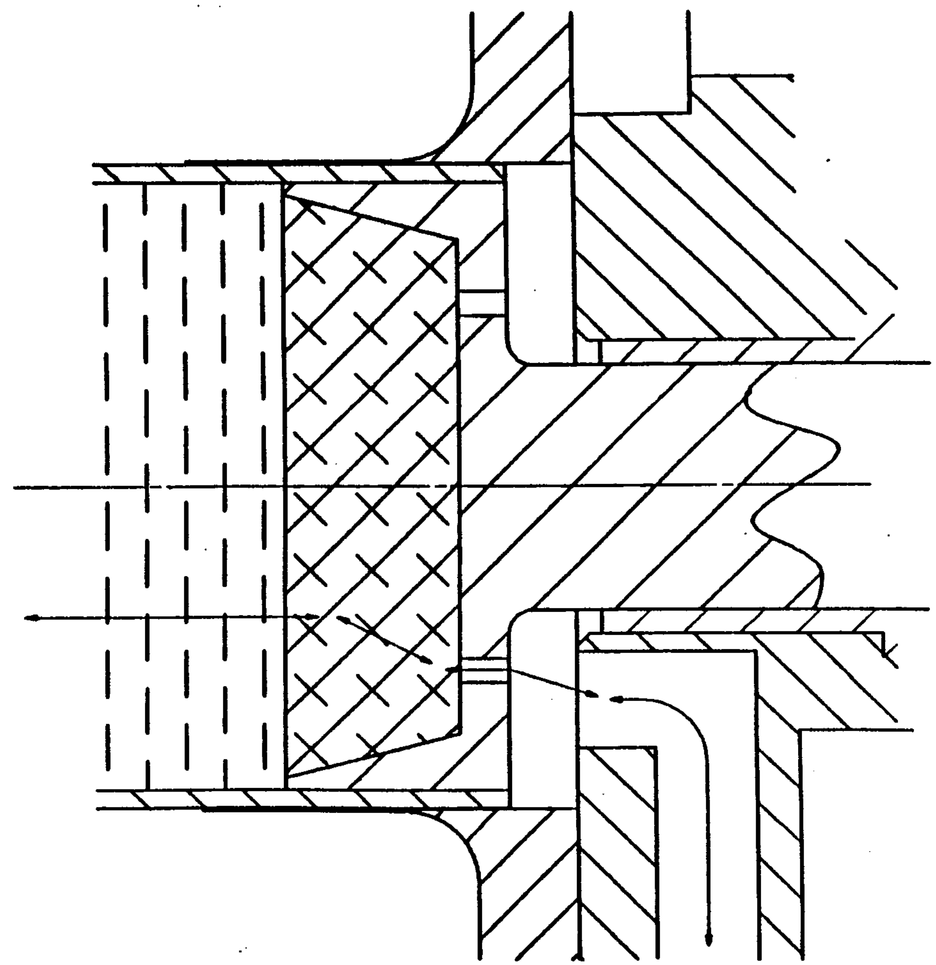
* Stresses at maximum stroke are quite low:

  - approximatly 25 Ksi at the thin section.
  - approximatly 35 Ksi at the inside spiral termination hole.

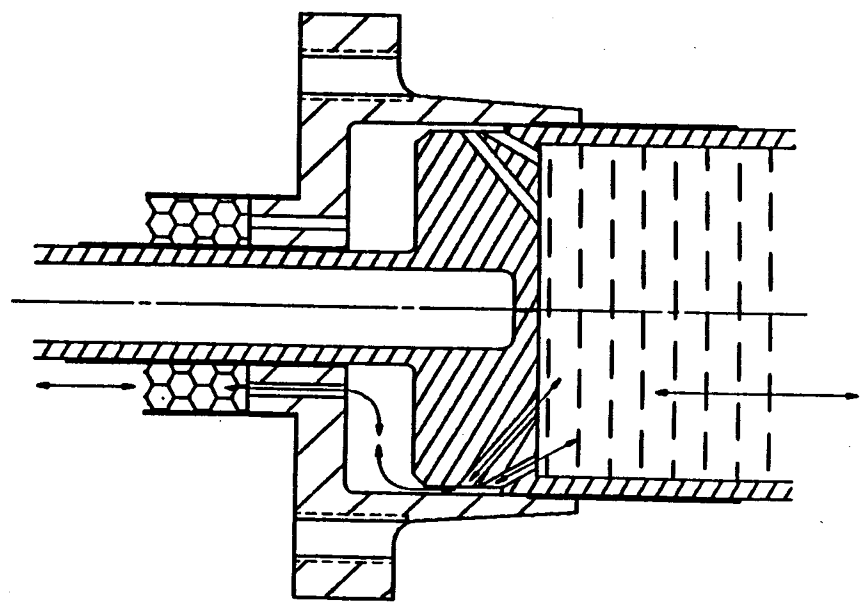
* For the 40 HZ design, an ideal design (minimizing radial deflections) is:

  - 12 springs in the forward stack (regenerator end).
  - 4 springs in the aft stack (target plate end).

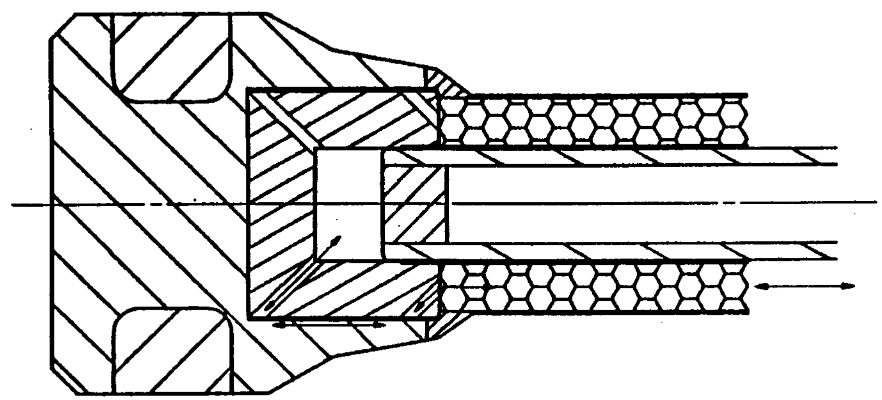
FIRST STAGE GAS FLOW PATHS



SECOND TO THIRD STAGE GAS FLOW PATHS



COLD END GAS FLOW PATHS



LEADING REGENERATOR CANDIDATES

- 3RD STAGE
  - "Composite" regenerator utilizing mixture of $ErAl_2$ / GdRh / Pb in sintered form
  - Layered regenerator utilizing sintered "plugs" of above
  - Perforated plate with integral rare earth materials (ACE)
- 2ND STAGE
  - Phosphor Bronze Screens
  - "Rolled" Screens to Reduce Porosity
  - Above plus SnPb alloy at 30 K - 50 K
  - Phosphor Bronze with Lead Coating
- 1ST STAGE
  - Stainless steel screens with graduated size distribution
  - "Rolled" Screens to Reduce Porosity

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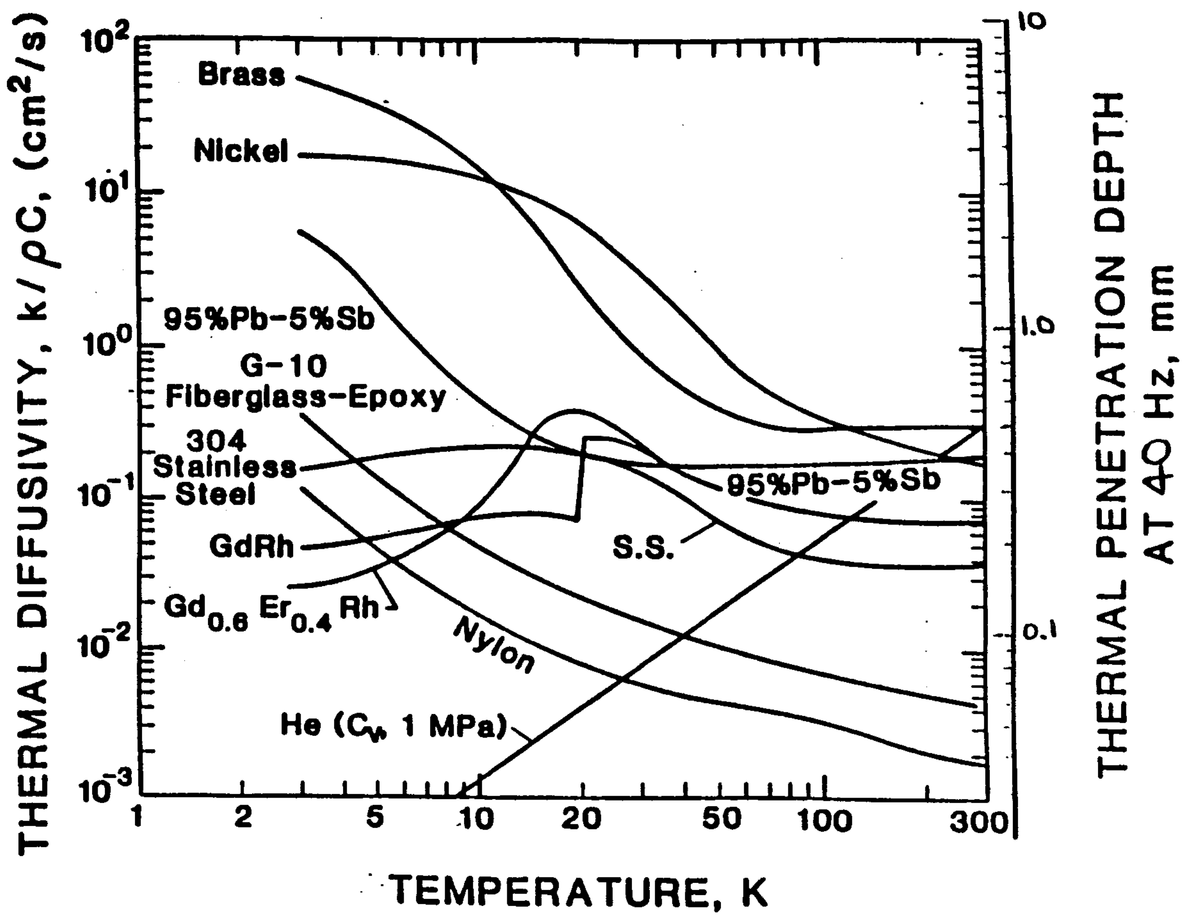
REGENERATOR MATERIALS, THERMAL PENETRATION DEPTH AT 40 HZ

Air Force
Phillips Laboratories
10 K CoDR



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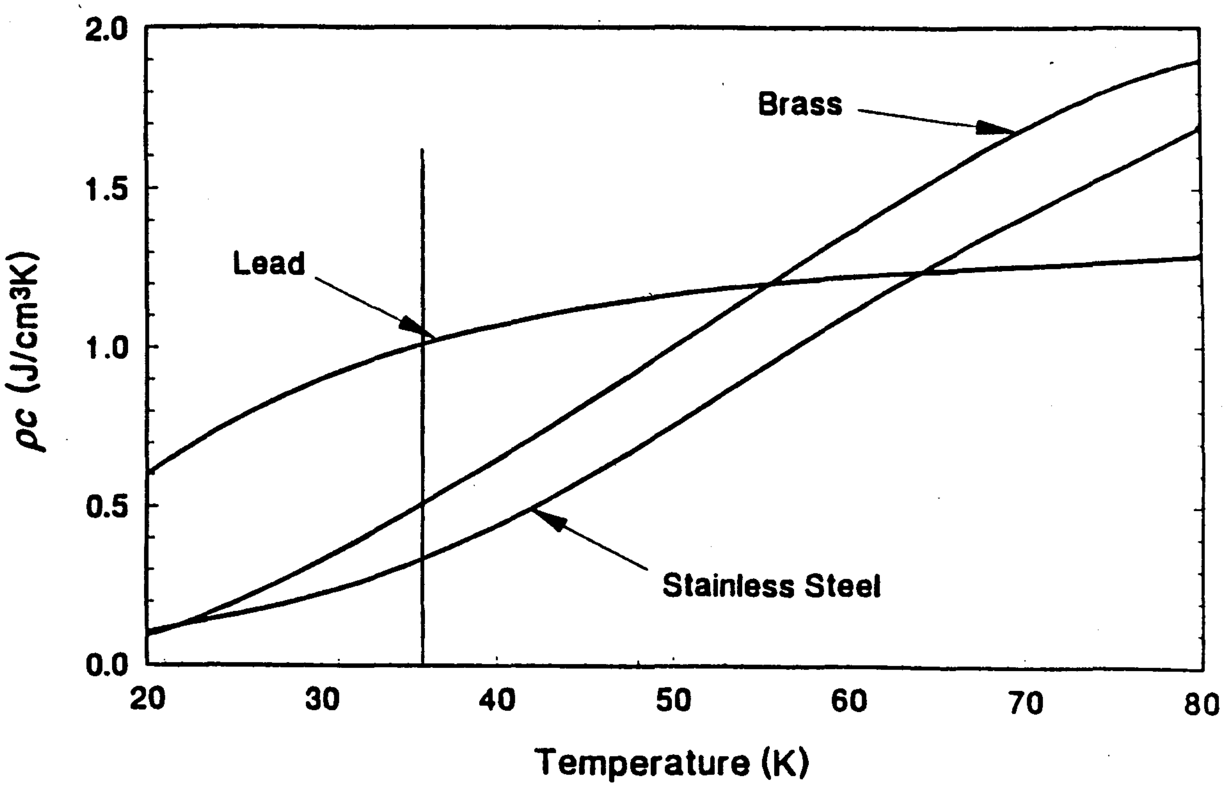
VOLUMETRIC HEAT CAPACITIES OF SECOND STAGE REGENERATOR CANDIDATES

Air Force
Phillips Laboratories
10 K CoDR



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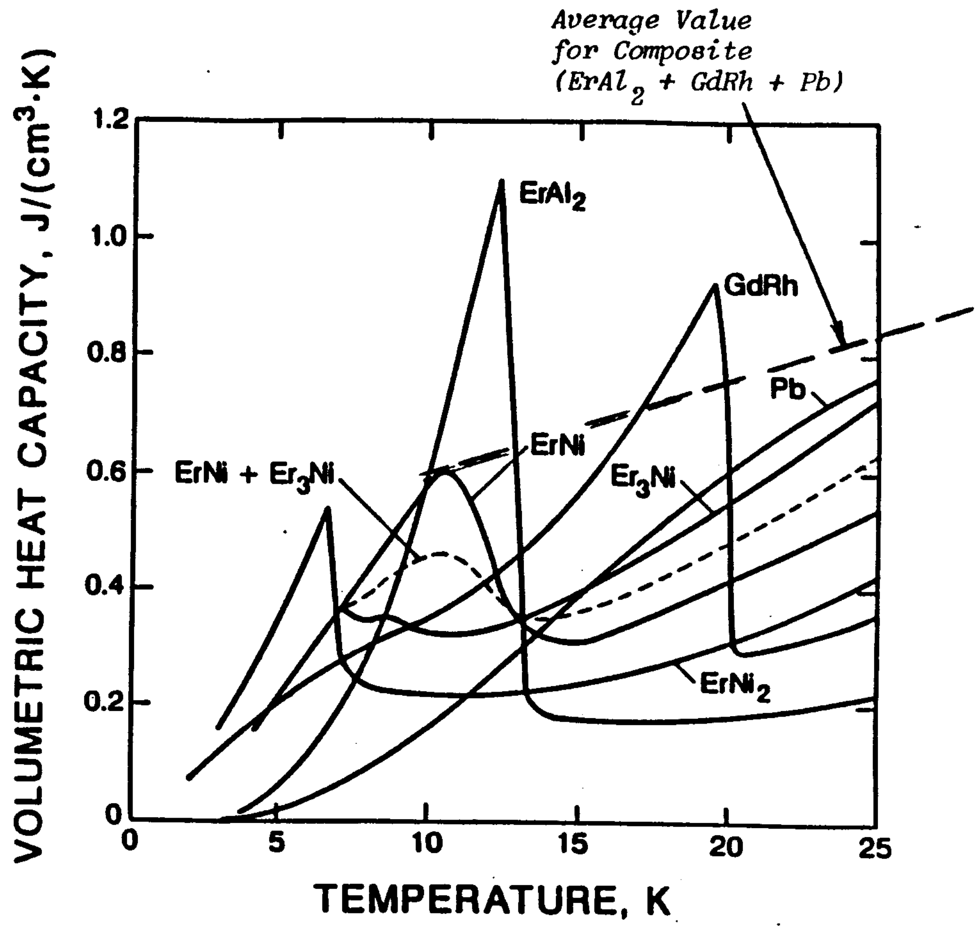
VOLUMETRIC HEAT CAPACITY OF COMPOSITE REGENERATOR

Air Force
Phillips Laboratories
10 K CoDR



REGENERATOR MATERIAL SOURCES 1/2

Alabama Cryogenic Engineering, Huntsville, AL
- Perforated Plates

AESAR, Johnson Matthey, Inc., Seabrook, NH
- Dy - 40 mesh and 250 um powder, ingot
- Er - 250 um powder, ingot
- Gd - 40 mesh and 250 um powder, ingot
- Nd - 250 um powder, ingot
- Rh - 22 and 60 mesh powder

CERAC/PURE Division of CERAC, Milwaukee, WI
- Dy - 40 mesh powder, 12 mm pieces
- Er - 40 mesh powder, 12 mm pieces
- Gd - 40 mesh powder, 12 mm pieces
- Nd - 40 mesh powder, 12 mm pieces

Howard Wire Cloth, Hayward, CA
- CRES wire cloth - various meshes
- Phosphor Bronze wire cloth - various meshes

Metallurgy Division of NIST, Gaithersburg, MD
- Er_3Ni - powder
- Rh - nitrided powder

REGENERATOR MATERIAL SOURCES 2/2

Rhone Poulec, Phoenix, AZ
- Er - ingot
- ErNi - ingot pieces
- Er3Ni - ingot pieces
- Gd - ingot
- GdRh - ingot pieces, 300 g buttons

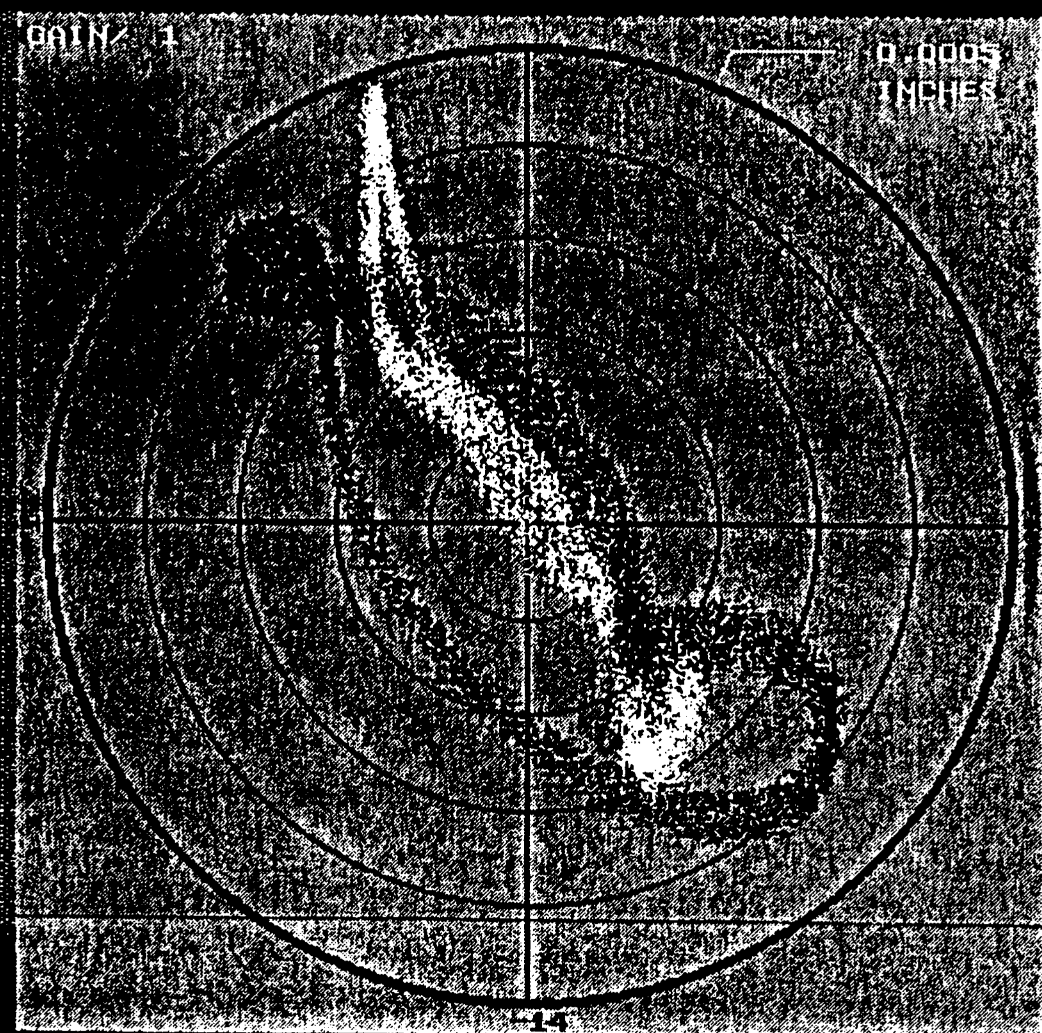
Toshiba, Westboro, MA
- Er3Ni - 0.18-0.45 mm powder

DISPLACER RISKS AND CONCERNS

RISK/CONCERN	RESPONSE
Maintain clearances during assembly.	Provide adjustment and means of measurement.
Maintain clearances during operation.	Model extensively with dynamic model including gas dynamics.
Proper gas flow, pressure drop and heat transfer.	Model with SRPM.
Heat dissipation at displacer hot end.	Model with SRPM, provide cooler transfer line and/or isothermalizer.
Uniform flow thru regenerator.	Provide flow diffuser.
Third stage regenerator lifetime.	Use sintered materials or perforated plates.

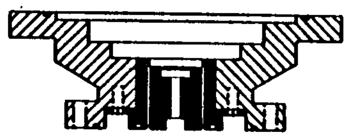
ALIGNMENT PROGRAM SUMMARY

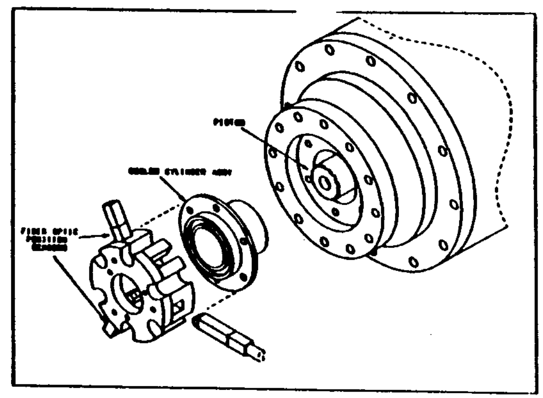
- A TECHNIQUE FOR MEASURING THE MOTION OF THE MOVING MASS HAS BEEN DEMONSTRATED IN THE LABORATORY
  - QUANTIFIES MAGNITUDE OF MOTION
  - ALLOWS EFFECTS OF ALIGNMENT EFFORT TO BE SEEN
  - CURRENT SET-UP LIMITED BY SPRING ARM MOVEMENT @ 50-HZ
  - TESTING CONTINUES TO DETERMINE SYSTEM SENSITIVITIES
- 80K BASELINE COMPATABLE WITH ALIGNMENT SCHEME
  - FIRST USE OF CENTERING DEVICE TO BE IMPLEMENTED ON SCRS BUILD

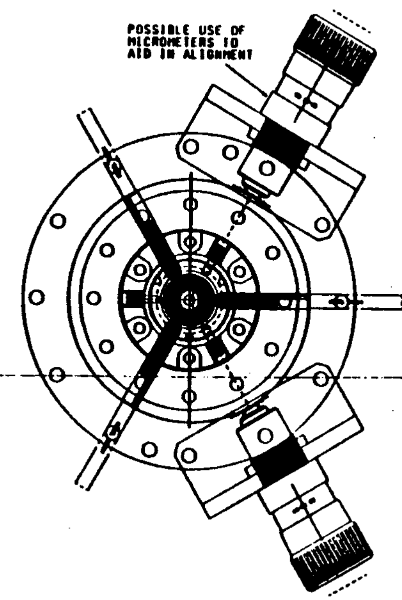


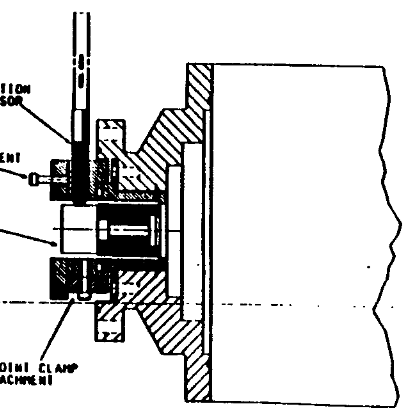
PISTON / CYLINDER ALIGNMENT TEST

PISTON/LINER CENTERING DEVICE









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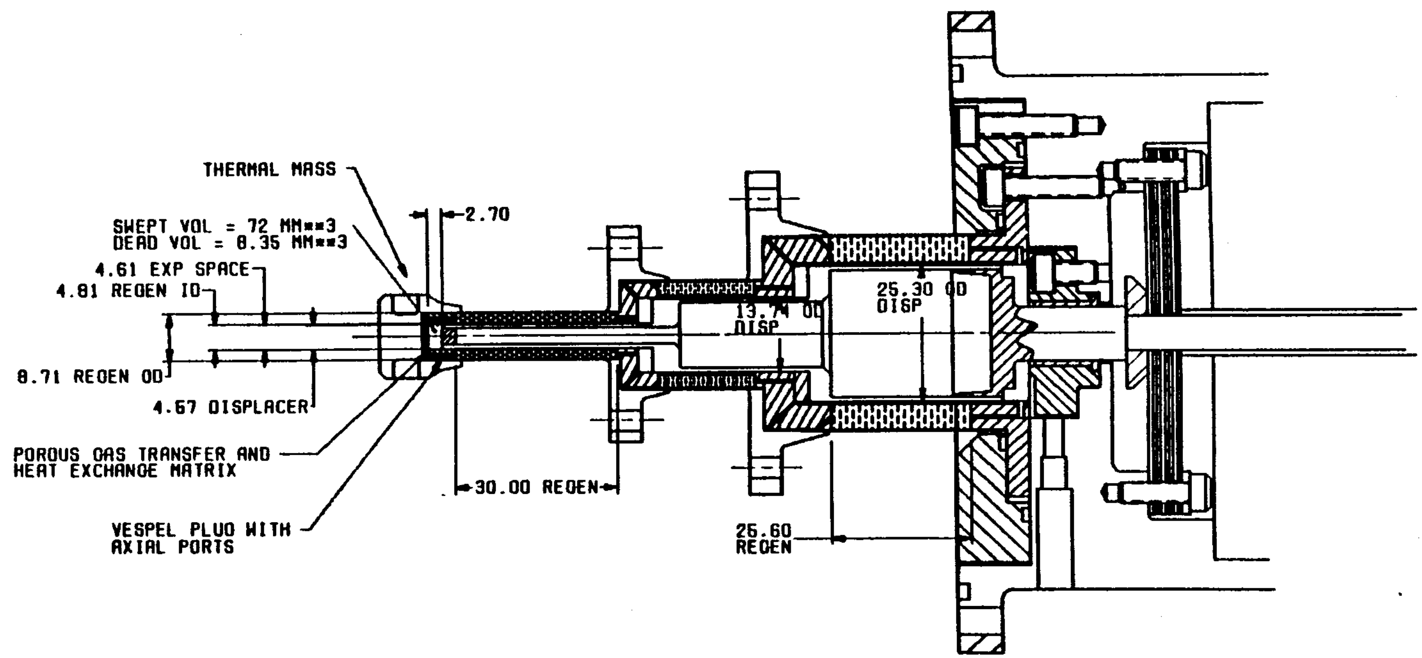
COLDFINGER CONCEPT WITH 3 STATIONARY REGENERATORS

Air Force
Phillips Laboratories
10 K Kick Off Meeting



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COOLING PERFORMANCE PREDICTIONS

SIDNEY W.K. YUAN

Lockheed
Lucas Aerospace

SRPM MODEL FEATURES
(PAGE 2 OF 2)

P/011464
NASA
80K PDR

- MODEL OUTPUT INCLUDES:
  - COMPLETE THERMODYNAMIC CHARACTERIZATION
    - -- TEMPERATURES
    - -- MASS FLOWRATES
    - -- PV-WORK (COMP & DISP)
    - -- PRESSURE DROPS
    - -- SYSTEM LOSSES
    - -- HEAT BALANCE AT EACH NODE
  - INPUT FOR DYNAMIC MODELING
    - -- PRESSURE -VS- TIME IN COMPRESSOR, DISPLACER
    - -- YIELDS GAS SPRING STIFFNESS AND DAMPING -VS- EXTENSION
  - INPUT FOR SINDA MODELING
    - -- SHUTTLED MASS FLOWRATES
    - -- INTERNAL HEATING TERMS
    - -- EFFECTIVE FILM COEFFICIENTS

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Lucas Aerospace

SRPM MODEL FEATURES

(PAGE 1 OF 2)

P/011464

NASA

80K PDR

- MODELS SPLIT-STIRLING CRYOCOOLER GEOMETRY
  - OVER 95 NODES
  - CONSERVATION OF MASS, MOMENTUM, ENERGY REQ'D AT EACH NODE
  - INCLUDES BLOW-BY AT CLEARANCE SEALS
  - ALLOWS FIRST-PRINCIPLE ASSESSMENT OF PARAMETER CHANGES

- MODELING FEATURES INCLUDE
  - SMITH'S COMPLEX NUSSELT NUMBER
  - KAYS & LONDON CORRELATIONS BETWEEN HEAT/MASS TRANSFER IN REGEN
  - AMAR & CANNON CALCULATION FOR PRESSURE DROP IN REGEN SCREENS
  - GORRING & CHURCHILL EMPIRICAL CONDUCTIVITY EQN FOR REGEN MATRIX
  - LAMINAR AND TURBULENT TRANSPORT IN TRANSFER LINE
  - ENTRANCE/EXIT EFFECTS IN ALL CONTRACTIONS/EXPANSIONS

GOVERNING EQUATIONS USED IN THE REGENERATOR

Gas Energy Balance Equation

$$\underbrace{\frac{h_t A}{LA_g}(T_m - T)}_{\text{heat transfer}} = \underbrace{\frac{\partial}{\partial x}\left[\left(\frac{m}{A_g}\right)h\right]}_{\text{enthalpy change}} - \underbrace{\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)}_{\text{thermal conduction}} + \underbrace{\frac{\partial}{\partial t}(\varrho u)}_{\text{energy storage}}$$

Matrix Energy Balance Equation

$$\underbrace{\frac{h_t A}{LA_g}(T - T_m)}_{\text{heat transfer}} = -\left(\frac{1 - n_g}{n_g}\right)\underbrace{\frac{\partial}{\partial x}\left(k\frac{\partial T_m}{\partial x}\right)}_{\text{thermal conduction}} + \underbrace{\frac{\partial}{\partial t}(\varrho u)}_{\text{energy storage}}$$

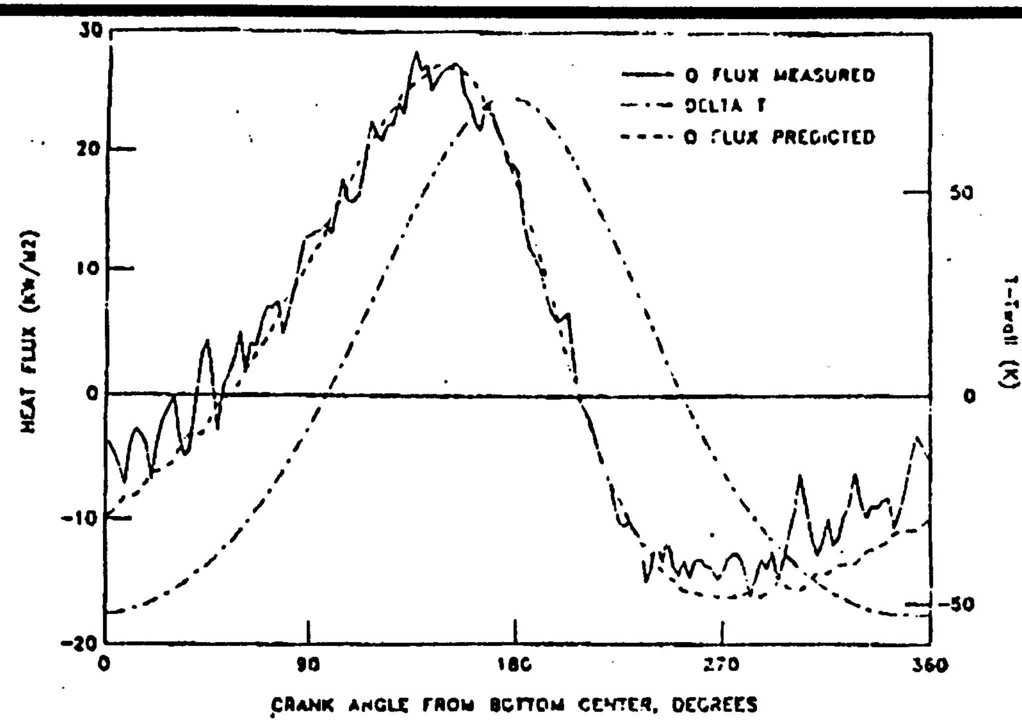
Continuity Equation

$$\underbrace{\frac{\partial}{\partial x}\left(\frac{m}{A_g}\right)}_{\text{mass divergence}} = \underbrace{-\frac{\partial \varrho}{\partial t}}_{\text{mass change}}$$

Conservation of Momentum

$$\underbrace{-\left(\frac{A}{LA_g}\right)\left(\frac{m}{A_g}\right)\frac{|\dot{m}|}{A_g}\frac{f}{2\varrho}}_{\text{friction force}} = \underbrace{\frac{\partial P}{\partial x}}_{\text{pressure gradient}} + \underbrace{\frac{\partial}{\partial x}\frac{1}{\varrho}\left(\frac{\dot{m}}{A_g}\right)^2}_{\text{momentum divergence}} + \underbrace{\frac{\partial}{\partial t}\left(\frac{m}{A_g}\right)}_{\text{momentum change}}.$$

SMITH'S COMPLEX NUSSELT NUMBER FOR HEAT TRANSFER

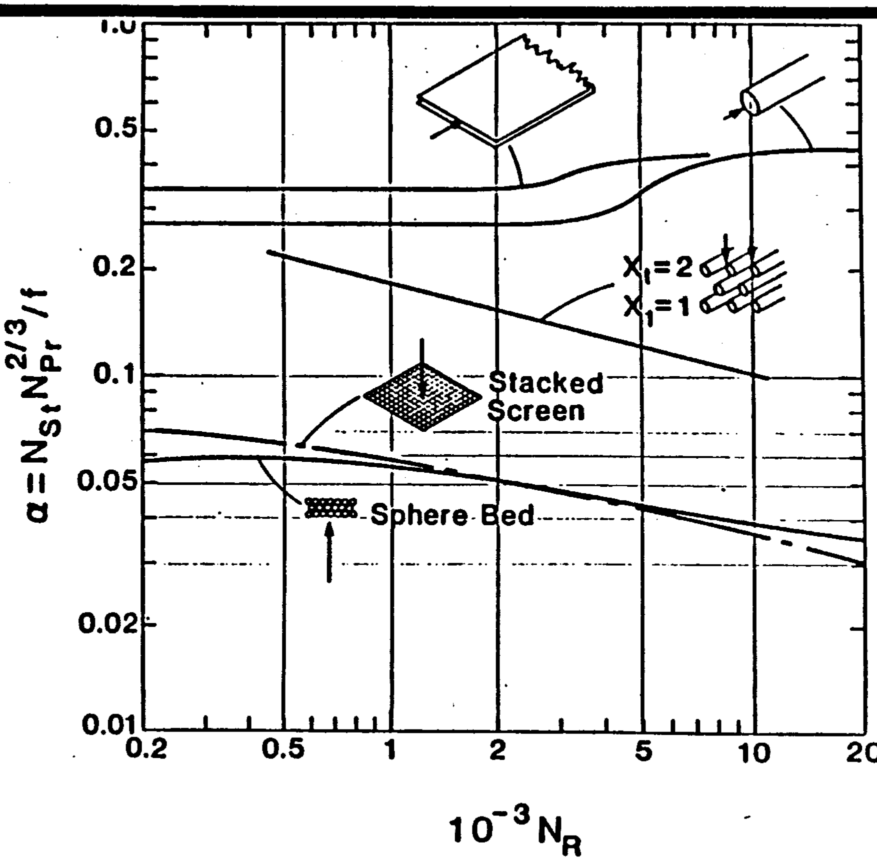


$$Q = [Nu_r(T-T_W) + (Nu_i/\omega)(dT/dt)]\ kA / D_h$$

Where

$$Nu_r = Nu_i = 0.98(PeD_h/L_s)^{0.59}$$

KAYS AND LONDON'S HEAT TRANSPORT IN HEAT EXCHANGERS



$N_{st} = h/C_p\ (m/A_g)$

$N_R = 2D_h / \mu(A_g/m)$

GORRING'S HEAT CONDUCTION OF HETEROGENEOUS MATERIALS

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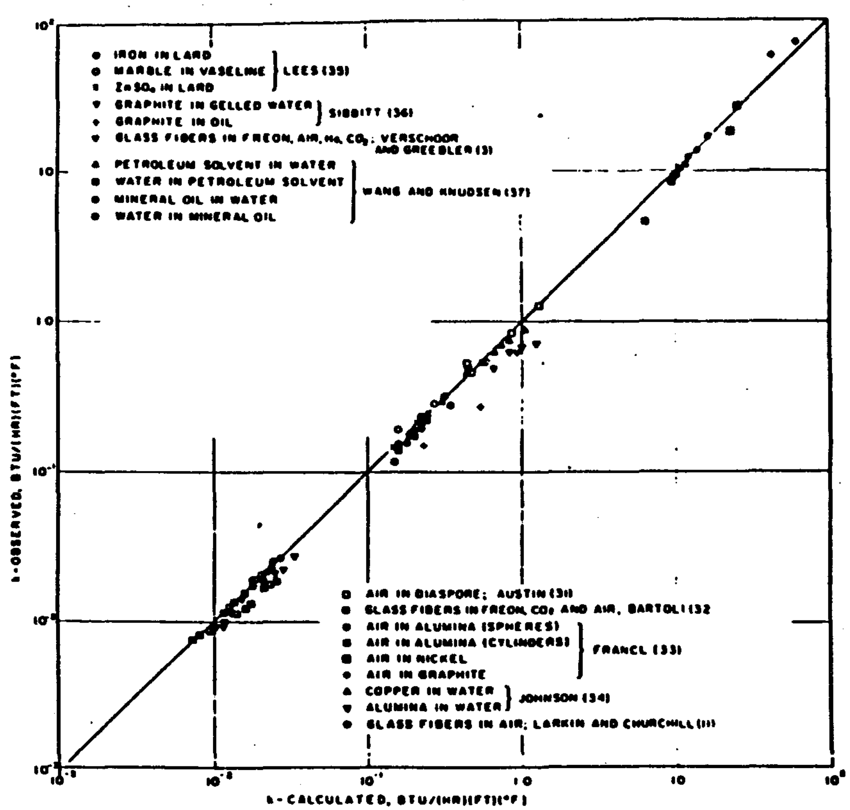


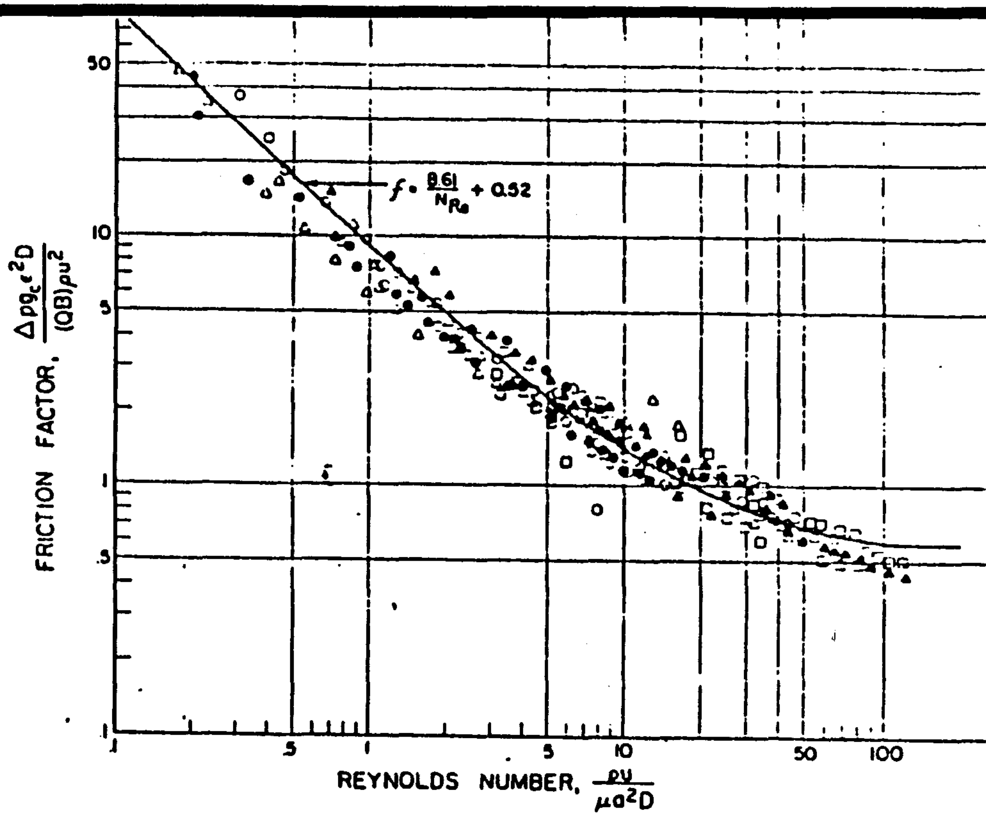
Figure 3. Comparison of predicted and experimental conductivities for dispersions.

$$KX = KG\left(\frac{\left(\frac{1 + (KM/KG)}{1 - (KM/KG)}\right) - FF}{\left(\frac{1 + (KM/KG)}{1 - (KM/KG)}\right) + FF}\right)$$

where

KX = thermal conductivity of the matrix, w/cm K
KG = thermal conductivity of the gas in the matrix, w/cm K
KM = thermal conductivity of the metal in the matrix, w/cm K
FF = fraction of matrix volume filled with solid

ARMOUR AND CANNON'S FRICTION FACTOR FOR PRESSURE DROP IN REGENERATOR



$f = (\alpha/Re_S) + \beta$

Where

$Re_S = \rho u / \mu a^2 D$

Nitrogen

△	Plain Square	Q = 1.0
○	Full Twill	
□	Fourdrinier	
▲	Plain Dutch	Q = 1.3
●	Twilled Dutch	

CRYOCOOLERS VALIDATED BY SRPM*

MACHINE	SIZE DISP. COMP.	TEMP.	HEAT LOAD EXPER/PRED.	COMMENTS
LOCKHEED/ LUCAS	7 mm 17 mm	65 K	0.5 W / 0.5 W	Detailed Validation, results published in Cryogenics Vol. 32, No 2, p143, 1992.
PHILIPS/NASA MAGNETIC BEARING	20 mm 52 mm	65 K	5 W / 5 W	Excellent prediction on input and heat load Results to be published in the 7th International Cryocooler Conference, Santa Fe, Nov. 1992
OXFORD UNIVERSITY	10 mm 20 mm	80 K	0.75 W / 0.72 W	Good agreement, results to be published in the Cryogenic Eng. Conf., 1993.
LMSC AIRS — CONF. A COMMON COMP SPACE	10 mm 20 mm	55 K	1.4 W / 1.3 - 1.8 W#	Limited data points, dependence on frequency and phase angle need further studies.
LMSC AIRS — CONF. B			0.69 - 1.08 W / 0.75 - 1.16 W	Excellent agreement on the prediction of net cooling as a function of compressor stroke.
LMSC AIRS — CONF. C COMMON COMP SPACE	10 mm 17 mm	55 K	1 W / 1 W	Preliminary results show good agreement between experimental data and predictiuon.

* DESCRIPTION OF THE COMPUTER MODEL CAN BE FOUND IN ADVANCES IN CRYOGENIC ENG. VOL.37 PART B, p1055, PLENUM PRESS, NEW YORK, 1992.

#PREDICTION PERFORMED BEFORE TEST DATA WAS AVAILABLE.

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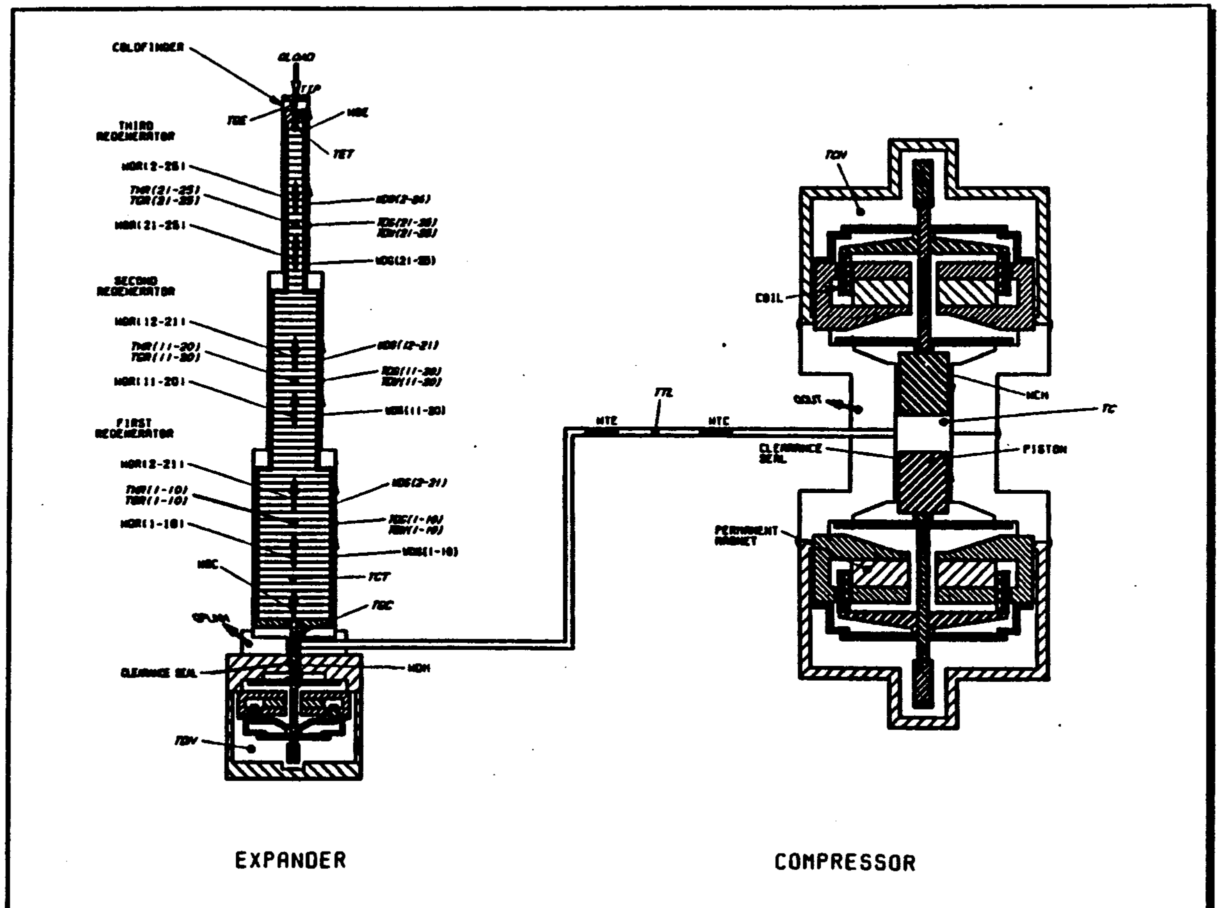
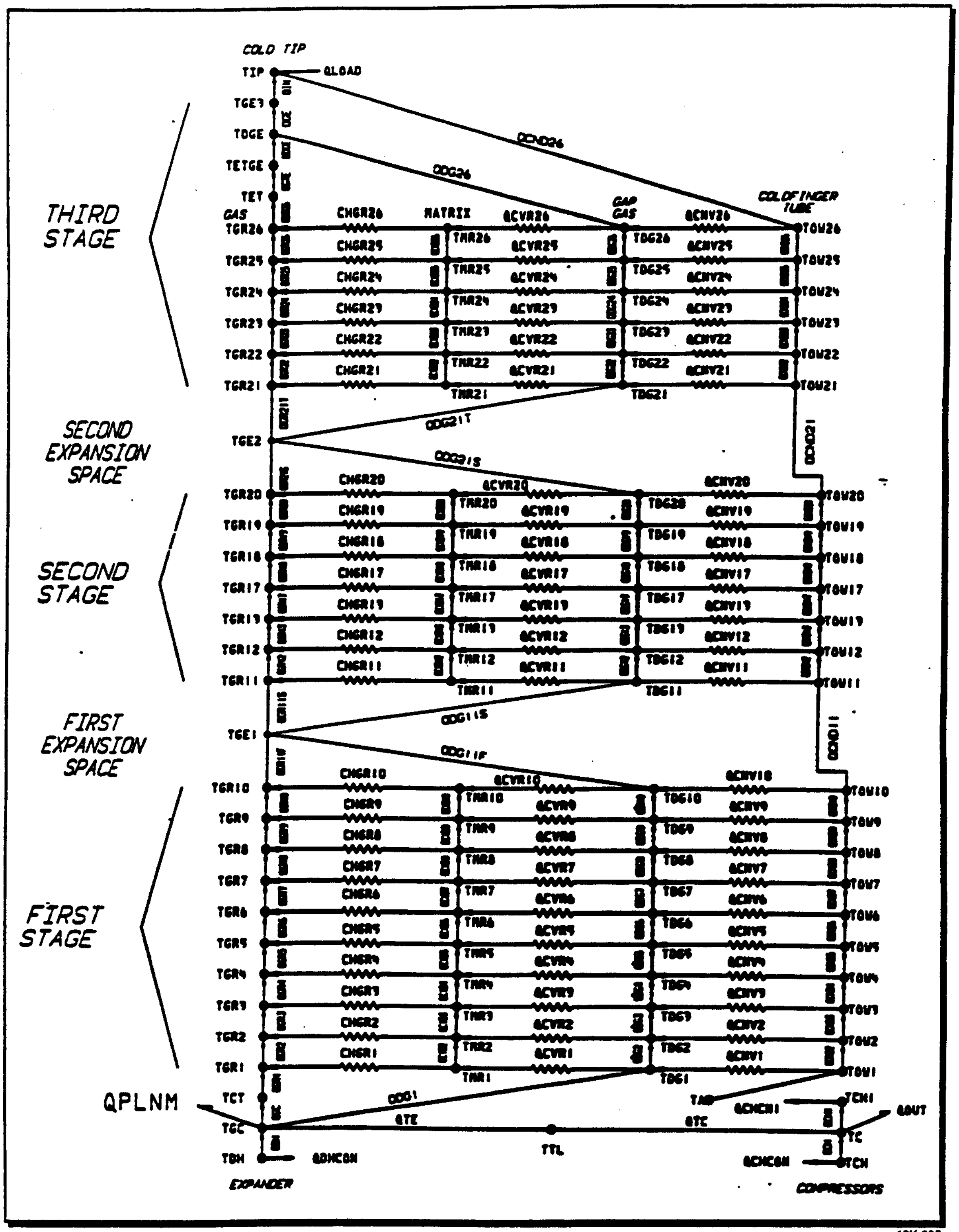
SCHEMATIC DIAGRAM OF THE 10K COOLER

Air Force
Phillips Laboratories
10K CoDR





10K-085

Three-stage Stirling nodal diagram

LMSC THERMODYNAMIC MODELING ON SRPM MODEL

- LMSC will set up compressor / displacer model of system. Principal parameters obtained from model will be:
  - Required Motor Force.
  - System Natural Frequency.
  - Energy Balance and Heat Dissipation.
  - Transfer Line Sizing.
  - Gas Passages and Porting for Displacer.
  - First Estimates of Cooling and Losses.

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SUMMARY OF RUNS

Air Force
Phillips Laboratories
10K CoDR

INPUT PARAMETERS:														OUTPUT PARAMETERS:							COMMENTS:
DATE OF RUN	ALG	Tcc / Tdc	Pfill	FREQ	Θ	Sc	Dc	Sd	L1/D1	L2/D2	L3/D3/G3	TLl / TLd	TGE1	TGE2	TGE3	ΔPc	∫PVc	NFREQ	PFORCE	QG	
(mo/day/yr)		(K)/(K)	(psia)	(Hz)	(deg)	(cm)	(cm)	(cm)	(cm/cm)	(cm/cm)	(cm/cm/cm)	(mm)/(mm)	(K)	(K)	(K)	(psia)	(watts)	(Hz)	(lb)	(W)	
RUN #1	4	300/300	220	10	60	3	3	0.44	2.56/2.5	1.79/1.36	3.0/.871/0.245	254/3.5	90	38	20						3rd stage Er3Ni
RUN #2	4	..	..	40	..	1.5	..	..	..	..	..	..	110	34	18						..
RUN #3	4	..	..	..	..	..	..	0.6	..	..	..	..	105.6	33.4	18.42						..
RUN #4	4	..	..	..	40	..	..	0.44	..	..	..	..	101.69	33	23						..
RUN #5	4	..	..	..	80	..	..	..	..	..	..	..	108.5	37.5	20.46						..
RUN #6	4	..	..	..	60	..	..	..	2.56/3.5	..	..	..	88.3	36.3	20.6						..
RUN #7	4	..	..	..	..	..	..	..	..	..	..	..	83.9	34.9	18.6						3rd stage Composit Material
RUN #8	1	..	..	..	..	..	..	..	..	..	..	..	91.7	35	16.4						..
RUN #9	1	..	..	..	..	..	..	..	4.56/2.5	..	..	..	97.85	36.55	16.28						
RUN#10	4	..	..	..	..	..	..	..	..	..	..	254/3.0	108.2	35	18.35						
RUN#11	4	..	..	..	..	..	..	..	2.56/4.5	..	..	254/3.5	89.3	36	15.2						
RUN#12	..	..	..	..	..	..	..	..	3.56/4.5	..	..	..	93.80	37.70	14.82						
RUN#13	..	..	..	..	..	..	..	..	..	..	..	..	93.90	37.50	15.10						change from screens to spheres in 3rd stage
RUN#14	..	..	..	20.00	..	..	..	..	2.56/2.5	..	..	..	101.00	37.70	16.00						
RUN#15	..	..	..	..	..	2.25	..	..	..	..	..	..	100.00	34.00	17.80						
RUN#16	..	..	..	..	..	..	..	0.60	..	..	..	..	114.00	33.74	16.00						
RUN#17	..	..	..	..	..	..	..	..	..	..	..	..	115.00	33.40	16.00						lower gap size in 1st & 2nd stage by 10 microns
RUN#18	..	..	..	40.00	..	1.50	4.00	0.40	4.56/3.5	..	..	..	93.30	37.94	18.20		541.00			0.30	
RUN#19	..	..	..	..	..	..	3.50	0.44	2.56/3.5	..	..	..	89.65	34.73	18.14		341.80	41.40	52.00	0.38	change 1st stage screens from 250 mesh to 325 mesh
RUN#20	..	..	..	..	..	..	..	0.60	..	..	..	..	88.81	33.31	16.04						
RUN#21	..	..	..	..	20.00	..	..	0.70	..	..	..	..	87.17	28.76	15.70		274.00	47.00	47.60	0.16	
RUN#22	..	..	..	..	50.00	..	..	..	..	..	3/1.3/0.45	..	87.50	33.40	13.80						
RUN#23	..	..	320.00	..	40.00	..	..	..	..	..	1.5/1.3/0.45	..	86.80	29.10	14.70		466.00	51.00	80.70	0.37	
RUN#24	..	..	220.00	..	..	..	..	..	..	..	3/1.3/0.45	..	82.00	32.90	15.00		347.00	45.00	56.50	0.40	change void fraction of 1st from 0.71 to 0.55
RUN#25	..	..	..	..	..	..	..	..	..	..	2/1.3/0.45	..	83.43	30.60	15.08		347.00	47.00	57.70	0.34	and second stage from 0.67 to 0.5
RUN#26	..	..	..	..	..	..	..	..	..	..	3/1.3/0.4	..	84.20	31.10	12.20		349.00	46.50	58.00	0.64	

Alg : Algorithm
Tcc : Temperature Compressor Case (TCH)
Tdc : Temperature Displacer Case (TDH)
Pfill : Fill Pressure (PPFILL)
FREQ : Compressor/Displacer Frequency (FREQ1/2)

Sc : Stroke Length of Compressor (XPC)
Dc : Compressor piston diameter (DPC)
Sd : Stroke Length of Displacer (XPE)
L1/D1 : 1st stage regenerator length over diameter
L2/D2 : 2nd stage regenerator length over diameter

TL1/TLd Transfer line length / I D
TGE1-TGE2-TGE3 1st, 2nd and 3rd stage expansion temperatures
∫PV c Net P-V Work/Cycle in Compression Space
NFREQ Natural frequency
PFORCE Motor force

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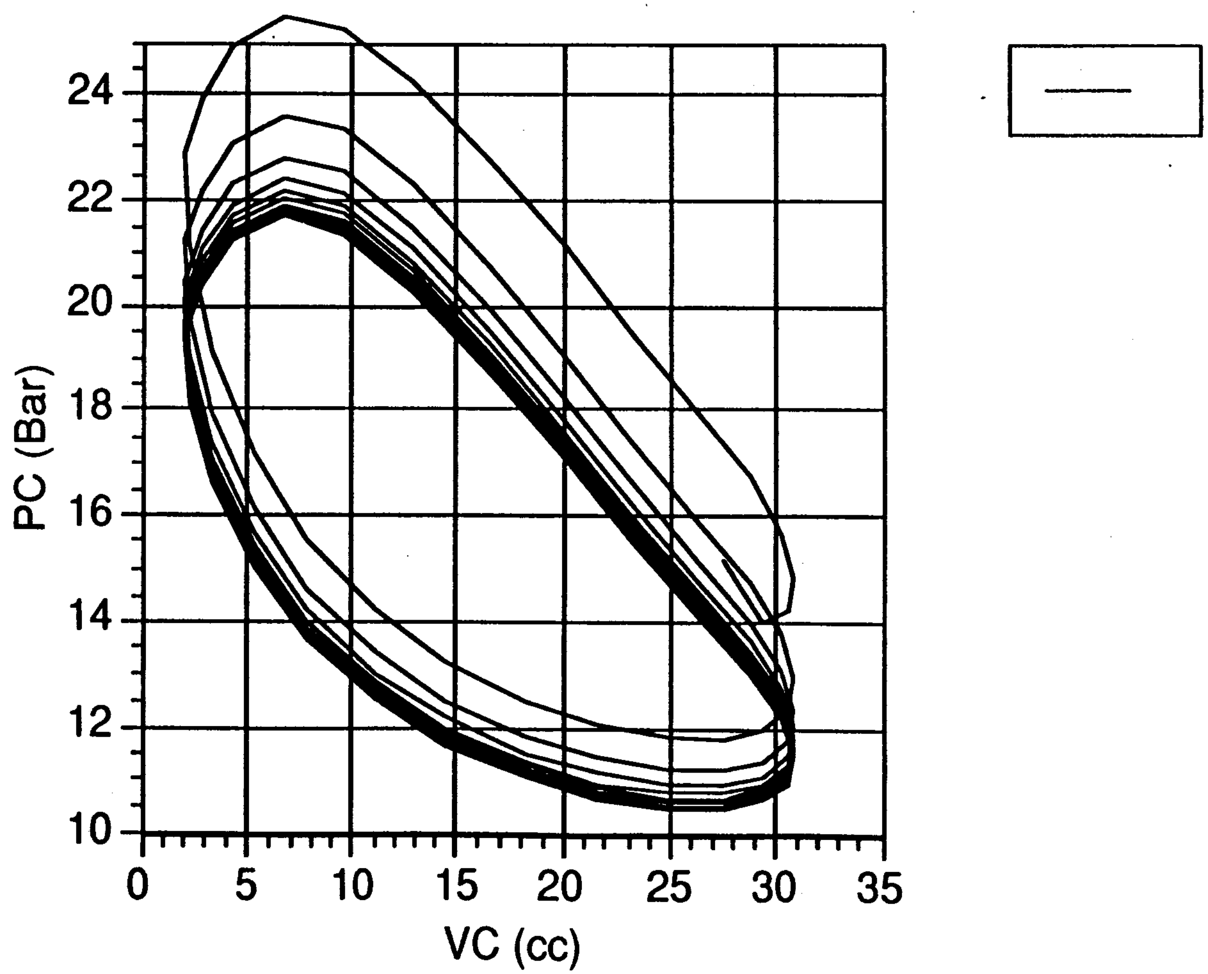
P-V IN THE COMPRESSION SPACE

Air Force
Phillips Laboratories
10K CoDR



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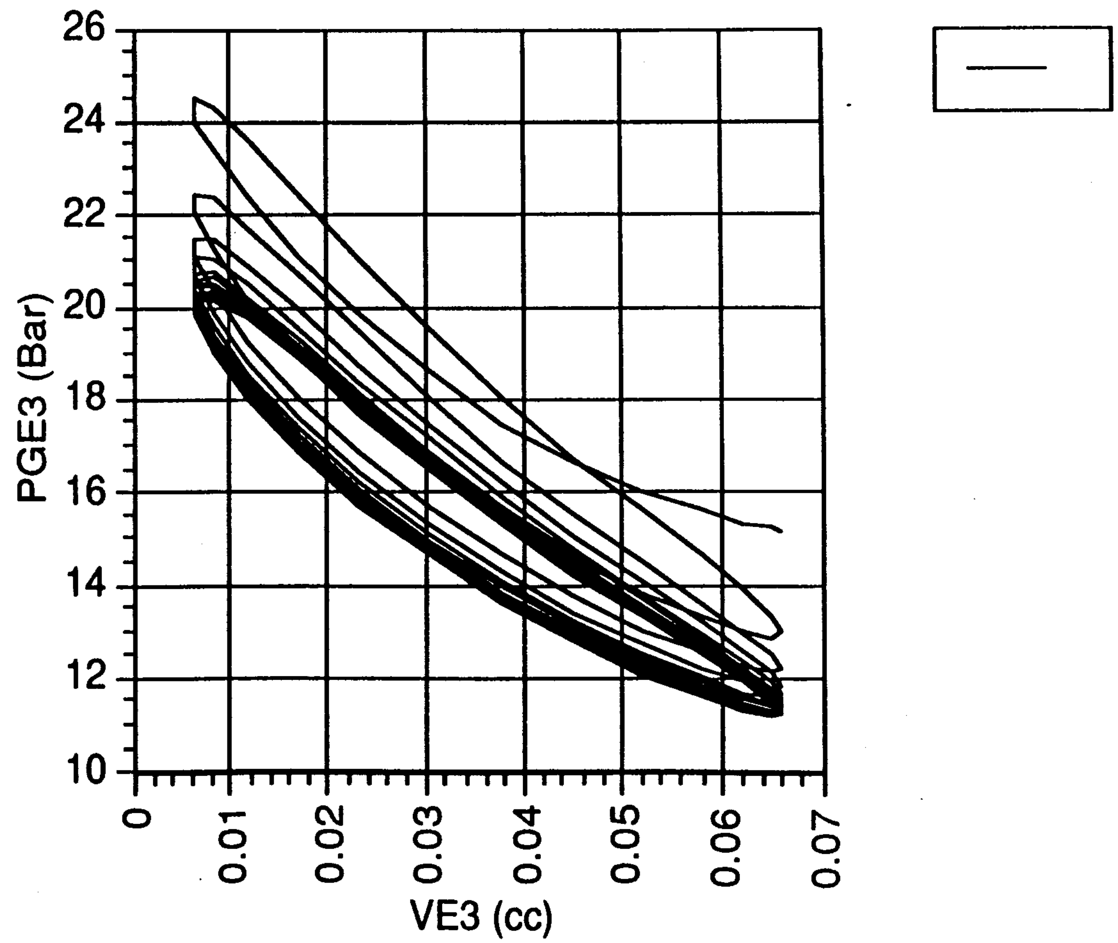
P-V IN THE THIRD EXPANSION SPACE

Air Force
Phillips Laboratories
10K CoDR



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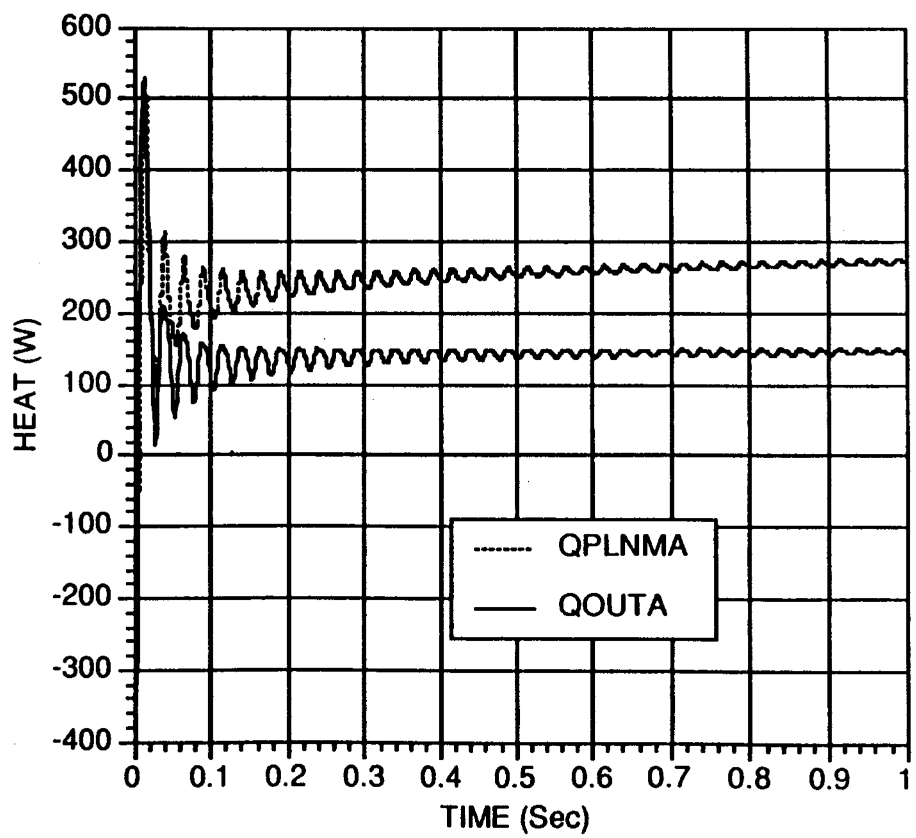
HEAT REJECTION AT COMPRESSOR & DISPLACER

Air Force Phillips Laboratories 10K CoDR



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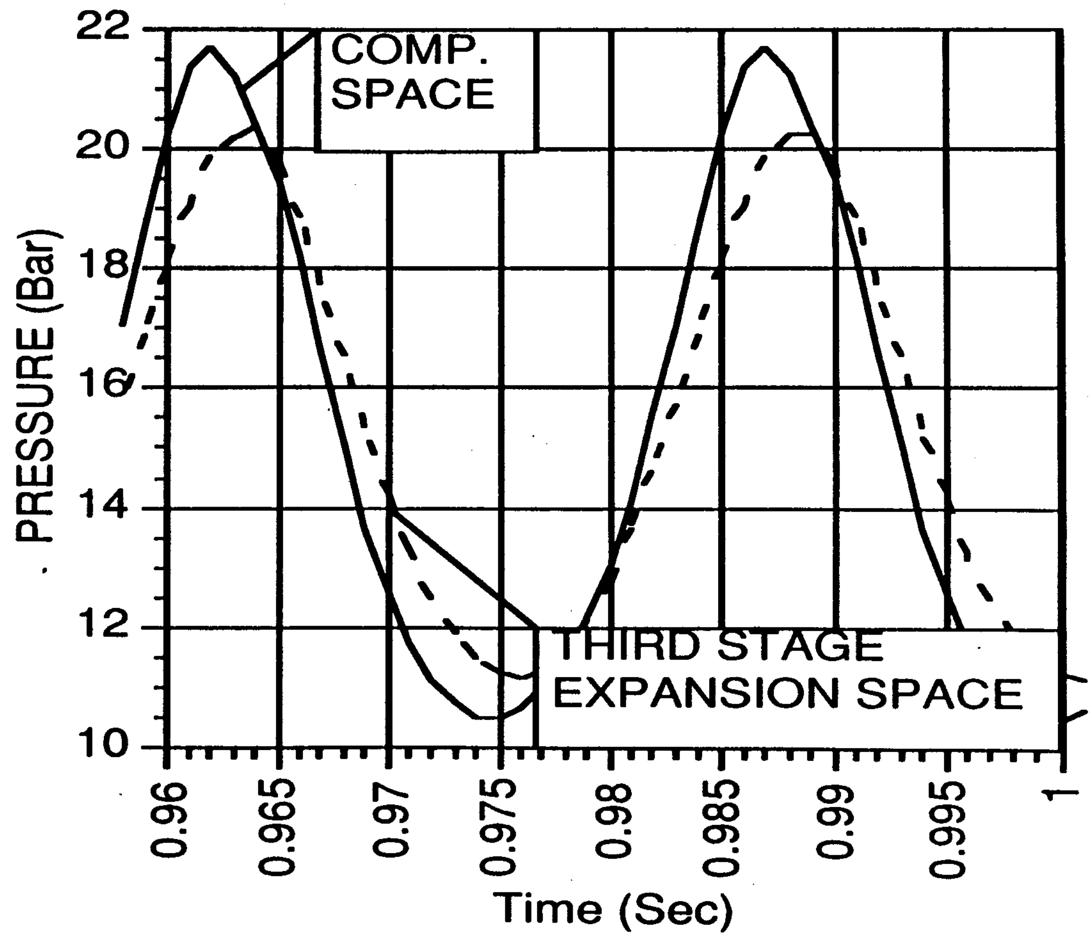
PRESSURE AT COMPRESSION SPACE & 3RD EXPANSION SPACE

Air Force
Phillips Laboratories
10K CoDR



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RAD

RUN SUMMARY

Air Force
Phillips Laboratories
10K CoDR

Net Ref. Power (W)	0.145, 2.0, 5.0
Displacer Stroke (mm)	7
Disp. Swept Volumes (cc)	0.137, 1.12, 5.7
Clearance Gaps (Microns)	17, 20, 30
Comp. Swept Vol. (cc)	28.86
Compressor P-V (W)	349
Operating Frequency (Hz)	40
Fill Pressure (Psia)	220

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SUMMARY OF DISPLACER LOSS TERMS FOR A TYPICAL RUN

Air Force
Phillips Laboratories
10K CoDR

	80K FIRST STAGE	35K SECOND STAGE	10K THIRD STAGE
Gross Cooling	35.2 W	6.5 W	0.64 W
Regenerator Loss	22.45 W	3.6 W	0.31 W
Blow-By Loss	7.75 W	0.9 W	0.185 W
Net Cooling	5 W	2.0 W	^0.15 W

ADDITIONAL WORK REQUIRED DURING NEXT PHASE

- Design for higher cooling margins
- Design for reduced power
- Design more efficient compressor motor
- Design better regenerators
- Optimize run conditions

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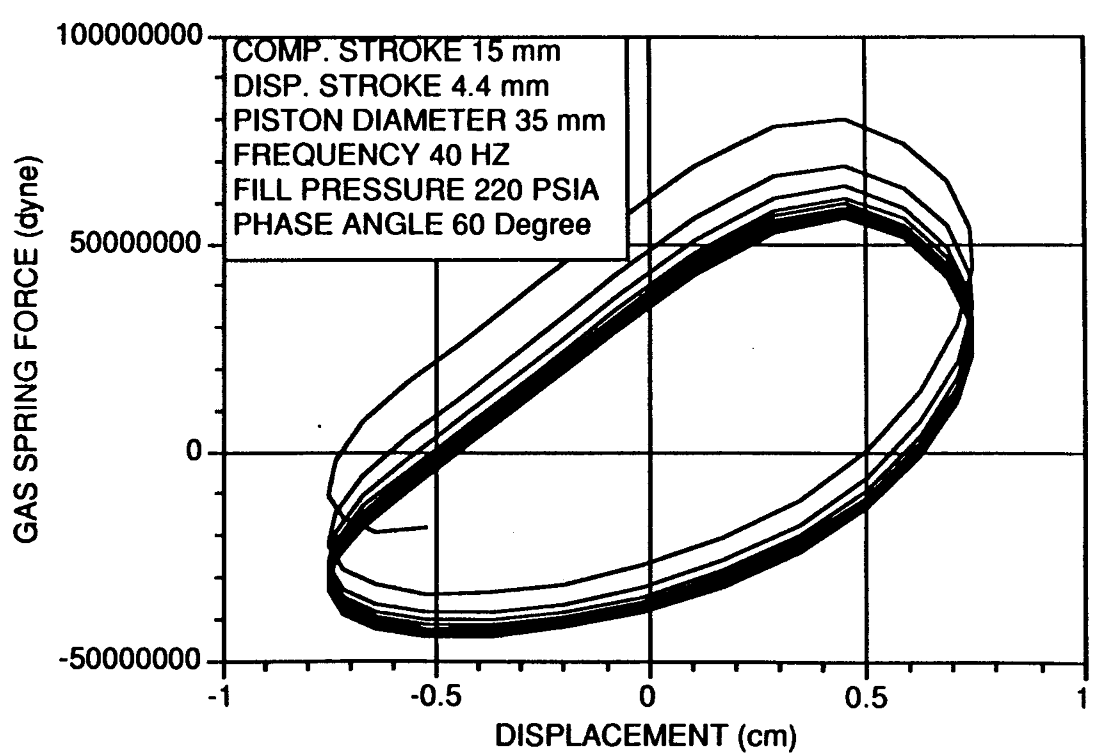
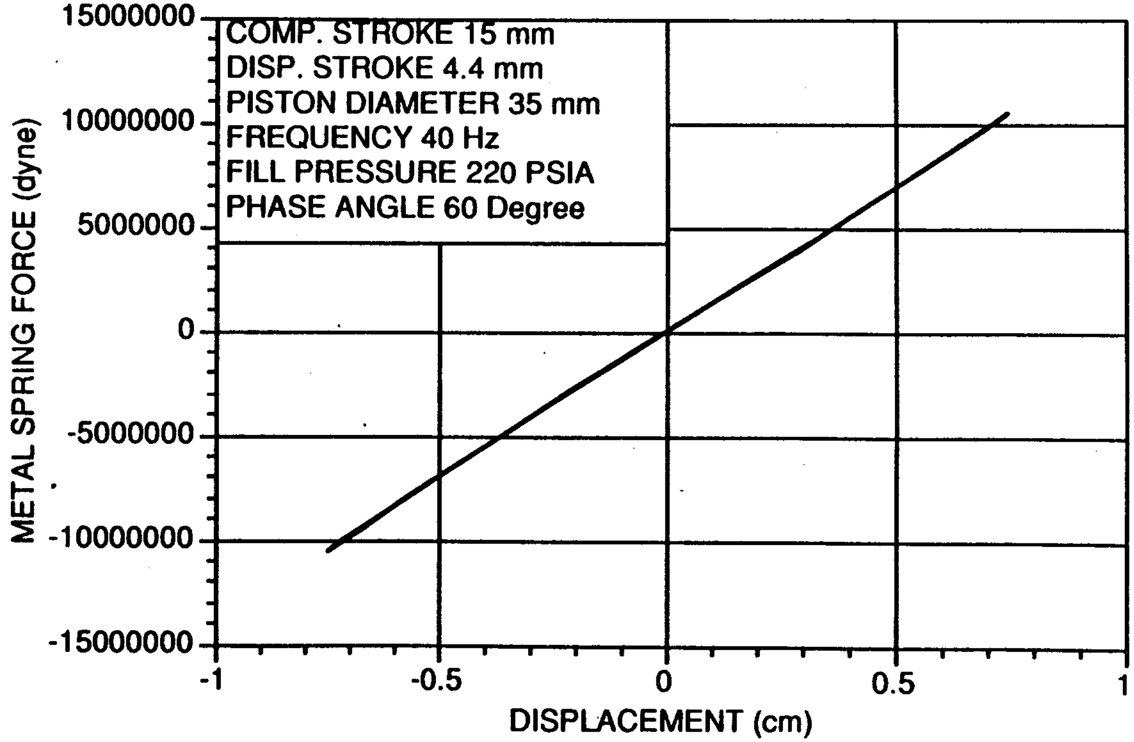
GAS SPRING FORCE IN COMPRESSOR

Air Force
Phillips Laboratories
10K CoDR



METAL SPRING FORCE



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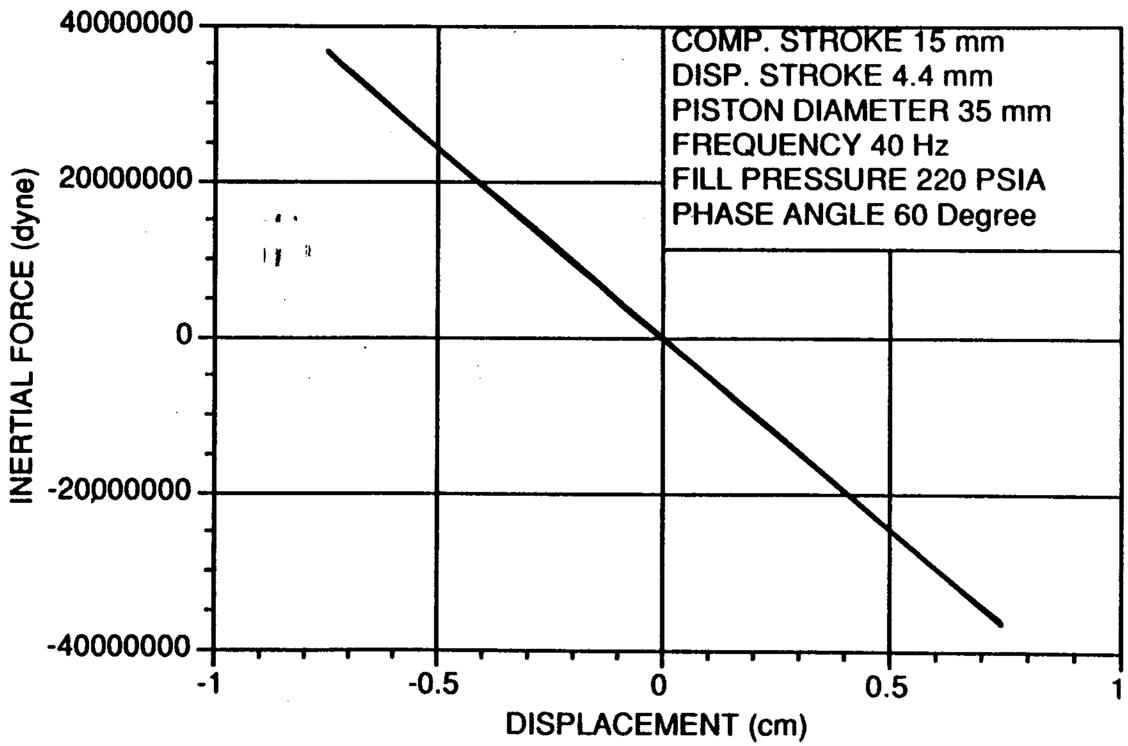
INERTIAL FORCE OF MOVING MASS

Air Force
Phillips Laboratories
10K CoDR

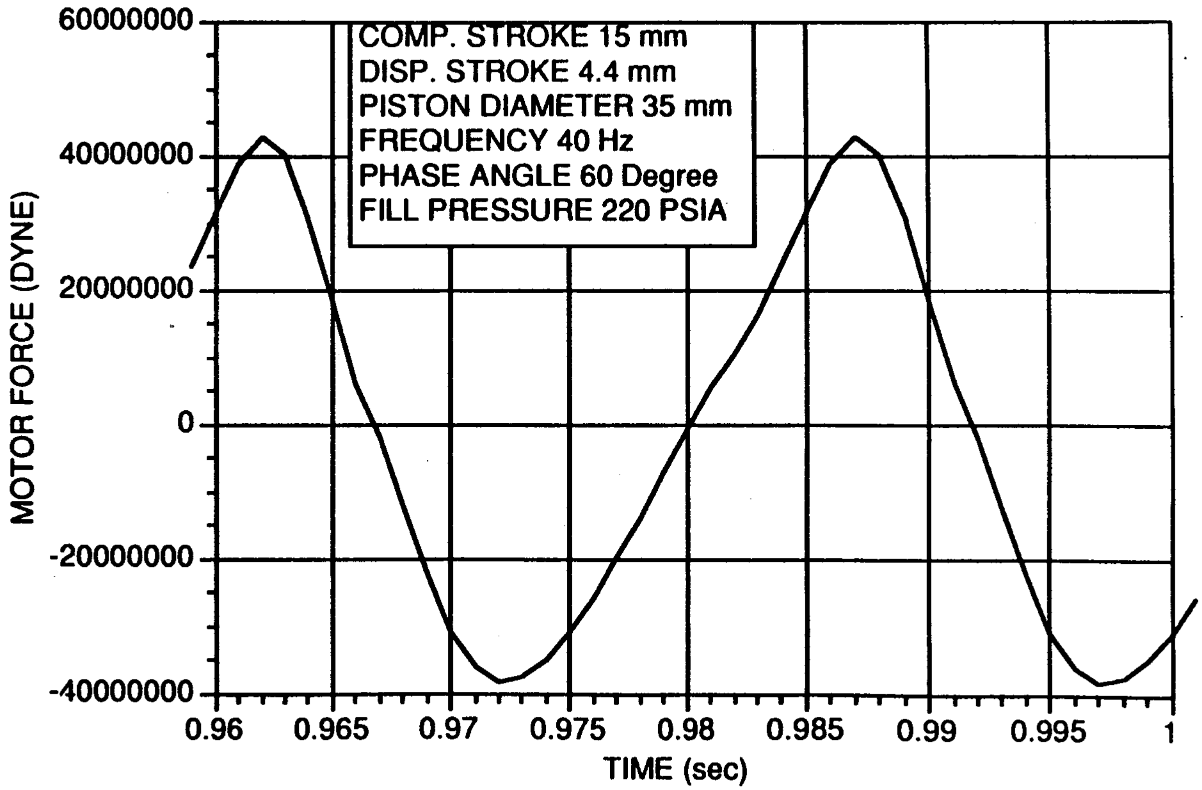


Lockheed

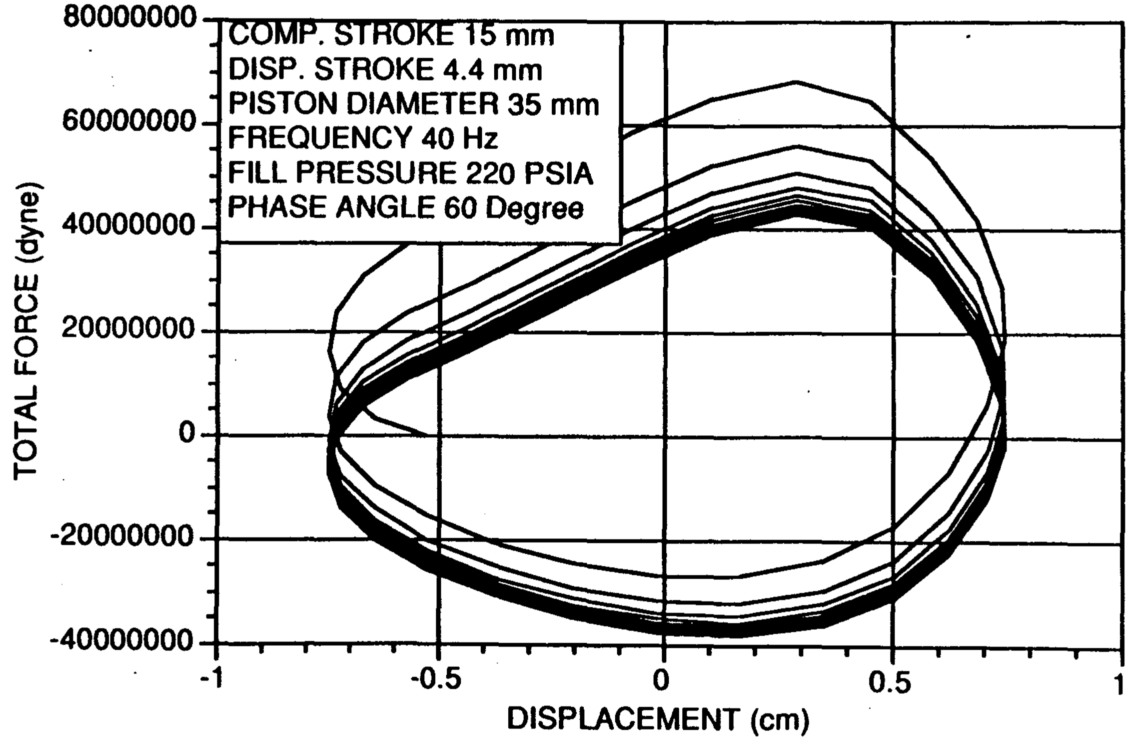
R&DD

TOTAL MOTOR FORCE VS. TIME

Air Force
Phillips Laboratories
10K CoDR



TOTAL MOTOR FORCE VS. DISPLACEMENT

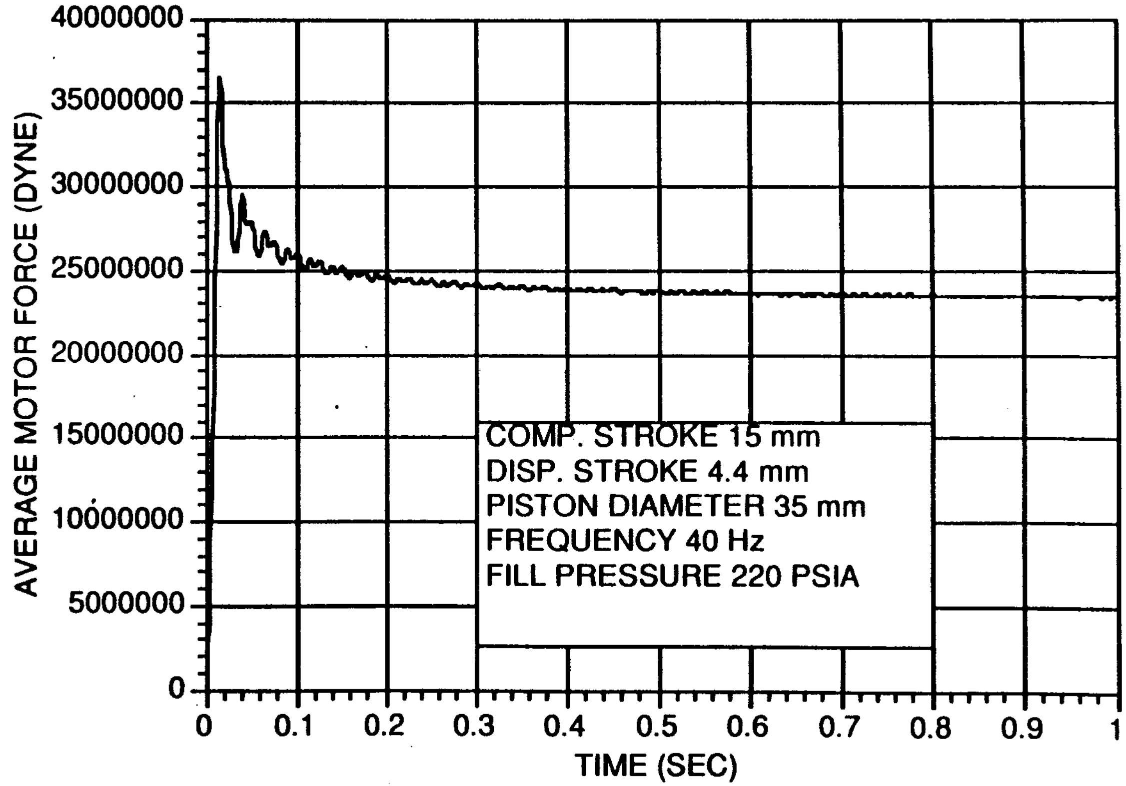


Lockheed

R&DD

AVERAGE MOTOR FORCE VS. TIME

Air Force
Phillips Laboratories
10K CoDR



NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)

DR. RAY RADEBAUGH

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)
DR. RAY RADEBAUGH

- Perform a design audit on the machine thermodynamics, using REGEN, REGEN 2 and REGEN3:
  - Complete iterations on the 40 Hz, 3 stage design initiated during proposal effort.
  - Perform parameter trades for fill pressure 10 to 30 Bar, operating frequency from 20 to 40 Hz and several regenerator trades including the perforated plate design (ACE)
  - Conduct additional trades indicated by above work. Candidate is the effect of lower temperatures on the 1st and/or 2nd stage on overall performance.
- Provide recommendations for regenerators, summarize state of the art and provide quote on sintered 3rd stage regenerator manufacture.
- Provide input to identification of critical components task and Phase 2 SOW.
- Provide Summary Report of work.

SUMMARY

- Low porosity regenerators improve performance significantly, particularly in 2nd and 3rd stages

3rd stage:	0.30 porosity spheres, 2 sizes
2nd stage:	0.55 porosity screen (flattened)
1st stage:	0.60 porosity screen (flattened)

- Optimum mean pressure is 1.5 MPa

- Minimum clearance gap occurs in 3rd stage

- Both 20 Hz and 40 Hz cases studied

- REGEN3.1 used for analysis of all regenerators

- Degradation factor of 0.85 used to convert isothermal PV expansion work to gross refrigeration power in each stage

- Real gas properties used in calculations

- Actual input PV power taken as 1.5 times calculated isothermal PV power to account for compressor losses

- Efficiency of 85% assumed for conversion of electrical to PV power in linear resonant compressor

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CONCLUSIONS FROM NIST

Air Force
Phillips Laboratories
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THREE STAGE STIRLING CAN EASILY MEET SPECIFICATIONS

40 HZ OPERATION PREFERRED BECAUSE OF SMALLER COMPRESSOR

427 W INPUT POWER WITH LARGE EXCESS COOLING POWER

387 W INPUT TO MEET REQUIREMENTS

20 MICRON CLEARANCE GAP FOR 3RD. STAGE

LOW POROSITY REGENERATORS NECESSARY FOR HIGH EFFICIENCY

20 Hz and 40 Hz Operation

	20 Hz	40 Hz
Temperature, K	10, 35, 80	10, 35, 80
Net Refr. Power	0.19, 3.41, 10.3	0.19, 3.27, 10.9
Stroke (mm)	6.0	4.4
Swept vol. (cm^3)	0.11, 0.82, 4.3	0.07, 0.44, 1.7
Clear. gap (μm)	23, 30, 40	20, 25, 35
Comp. swpt vol.	26	19
Input el. power	408 W	427 W
% input power	12%, 28%, 60%	20%, 29%, 51%

Nomenclature:

V_e (cm^3)	Expansion space swept volume (or volume of gas passing through regen.)(magn.&phase)
d (mm)	Diameter of displacer
t_w (mm)	Thickness of cylinder wall
t_g (μm)	Thickness of gap between displacer and cylinder wall
Regen. mat.	Regenerator matrix material
Porosity	Porosity of regenerator matrix
Mesh	Mesh size of screen used for regenerator matrix (if screen is used)
Par. dia(μm	Diameter of sphericle particles in regenerator matrix (if spheres are used)
A_t (cm^2)	Total cross sectional area of regenerator (matrix plus gas)
D (mm)	Diameter of regenerator
L (mm)	Length of regenerator
V_{rg} (cm^3)	Volume of gas in regenerator
V_{rg}/V_e	Ratio of regenerator gas volume to expansion space swept volume
P_r	Pressure ratio at cold end of regenerator
P_1/P_0	Ratio of dynamic pressure amplitude to the mean pressure
$\Delta P/P_0$	Ratio of average pressure drop in one direction to the mean pressure
T_r (K)	The log-mean temperature of the regenerator, $T_r = (T_h-T_c)/\ln(T_h/T_c)$
$\dot{m}_e$ (g/s)	Mass flow rate into the expansion space volume (magnitude and phase)
$\dot{m}_c$ (g/s)	Mass flow rate at the cold end of the regenerator (magnitude and phase)
$\dot{P}V_{rg}/RT_r$(g/s	Rate of change of mass within the regenerator due to pressure change (magn. and phase)
$\dot{m}_h$ (g/s)	Mass flow rate at hot end of regenerator (magnitude and phase)
$\dot{W}_c$ (W)	Total work flow at cold end of regenerator
$\dot{W}_e$ (W)	Work flow into expansion space volume (isothermal conditions)
$\dot{Q}_{em}$ (W)	Maximum gross refrigeration power in expansion space (includes real gas effects)
$\dot{Q}_e$ (W)	Actual gross refrigeration power in practical system
$\dot{Q}_{reg}$ (W)	Regenerator loss due to ineffectiveness of regenerator
$\dot{Q}_c$ (W)	Conduction loss in regenerator matrix
$\dot{Q}_{ct}$ (W)	Conduction loss in tube (pressure confining tube)
$\dot{Q}_{cd}$ (W)	Conduction down displacer (excluding any regenerator matrix)
$\dot{Q}_g$ (W)	Loss due to flow in gap between displacer and cylinder
$\dot{Q}_s$ (W)	Shuttle heat loss
$\dot{Q}_{net}$ (W)	Net refrigeration power
$\dot{W}_h$ (W)	Work flow at hot end of regenerator (neglecting pressure drop)
$\dot{W}_{h\Delta P}$ (W)	Work flow at hot end of regenerator (including pressure drop in regenerator)
$\dot{W}_{ce}$ (W)	Compressor PV work required to provide flow work into expansion space volume
$\dot{W}_{co\ total}$ (W)	Sum of compressor PV work required for specified stage plus all colder stages
REGEN3.1	Run number from REGEN3.1 analysis used for these calculations
Factor	Factor that is used to multiply the mass flows, cross-sectional areas, volumes, and powers in the REGEN3.1 analysis to adjust to the size needed for this case

Table 4. Characteristics of cold stages, 40 Hz, 1.5 MPa, 4.4 mm stroke.

Parameter	3rd Stage 10 K, 0.15 W	(Phase) (deg)	2nd Stage 35 K, 2 W	(Phase) (deg)	1st Stage 80 K, 5 W	(Phase) (deg)	Warm end 300 K
V_e (cm^3)	0.071	-133	0.436	-133	1.668	-133	2.195
d (mm)	4.53		12.11		25.20		25.20
t_w (mm)	0.41		0.41		0.41		
t_g (μm)	20		25		35		
Regen. mat.	composite		phos. bronze		S.S.		
Porosity	0.30		0.55		0.60		
Mesh			250		325		
Par. dia(μm	183						
A_f (cm^2)	0.900		0.840		3.78		
D (mm)	10.70		10.34		21.94		
L (mm)	30.0		25		30		
V_{rg} (cm^3)	0.81		1.155		6.80		
V_{rg}/V_e	11.41		2.65		4.03		
P_r	1.700		1.735		1.798		1.889
P_1/P_0	0.2593		0.2687		0.2852		0.3077
$\Delta P/P_0$	0.00939		0.0165		0.0225		0.0200
T_r (K)	19.96		54.4		166.4		300.0
$\dot{m}_e$ (g/s)	0.81	-32	0.89	33	1.63	29	
$\dot{m}_r$ (g/s)	0.81	-32	1.43	18	2.70	11	
$\dot{P}V_{rg}/RT_r$(g/s	1.91	90	1.04	90	2.12	90	
$\dot{m}_h$ (g/s)	1.13	58	1.82	47	3.56	43	
$\dot{W}_r$ (W)	1.50		14.39		66.34		
$\dot{W}_e$ (W)	1.50		8.14		34.17		48
$\dot{Q}_{rm}$ (W)	1.52		7.75		33.21		
$\dot{Q}_r$ (W)	1.29		6.59		28.23		
Q_{reg} (W)	0.76		3.15		10.05		
$\dot{Q}_c$ (W)	0.12		0.08		2.57		
$\dot{Q}_{ct}$ (W)	0.02		0.18		2.92	(1.19,Ti)	
$\dot{Q}_{cd}$ (W)	0.00		0.02		0.44		
Q_g (W)	0.13		0.48		0.63		
$\dot{Q}_s$ (W)	0.07		0.51		6.87		
$\dot{Q}_{net}$ (W)	0.19		3.27		9.17	(10.90,Ti)	
$\dot{W}_h$ (W)	6.03		30.91		242.2		213
$W_{h\Delta P}$ (W)	6.25		32.81		261.3		213
$\dot{W}_{co}$ (W)	60.7		90.8		157.0		
$\dot{W}_{co\ total}$ (W)			151.5		308.5		261
REGEN3.1	#922		#960		#957		
Factor	1.50		0.70		0.90		

Table 4b. Characteristics of aftercooler and compressor, 40 Hz, 1.5 MPa.

Parameter	Aftercooler 300 K	(Phase)	Conn. tube 320 K	(Phase)	Compressor 320 K	(Phase)	Electrical
V_{co} (cm^3)					19	-203	
d (mm)						(α=70°)	
t_w (mm)						(θ^*=23°)	
t_r (μm)						(θ=38°)	
Regen. mat.	copper						
Porosity							
Mesh							
Par. dia(μm							
A_r (cm^2)							
D (mm)							
L (mm)							
V_{rg} (cm^3)							
V_{rg}/V_o							
P_r	1.889				1.975		
P_1/P_0	0.3077				0.3277		
$\Delta P/P_0$	0.020						
T_r (K)	310				320		
$\dot{m}_o$ (g/s)							
$\dot{m}_c$ (g/s)	3.72	55					
$\dot{P}V_{rg}/RT_r$(g/s	0.2	90					
$\dot{m}_h$ (g/s)	3.87	57					
$\dot{W}_c$ (W)	213						
$\dot{W}_o$ (W)					4.2		4.9
$\dot{Q}_{rm}$ (W)							
$\dot{Q}_r$ (W)							
$\dot{Q}_{reg}$ (W)							
$\dot{Q}_c$ (W)							
$\dot{Q}_{ct}$ (W)							
$\dot{Q}_{cd}$ (W)							
$\dot{Q}_z$ (W)							
$\dot{Q}_o$ (W)							
$\dot{Q}_{net}$ (W)							
$\dot{W}_h$ (W)	227				363		
W_{hAr} (W)	242				363		427
$\dot{W}_{co}$ (W)							
$\dot{W}_{co\ total}$ (W)	(261)				(392)		(461)
REGEN3.1							
Factor							

Table 5. Characteristics of cold stages, 40 Hz, 1.5 MPa, 4.4 mm stroke, smaller 1st.

Parameter	3rd Stage 10 K, 0.15 W	(Phase) (deg)	2nd Stage 35 K, 2 W	(Phase) (deg)	1st Stage 80 K, 5 W	(Phase) (deg)	Warm end 300 K
V_e (cm^3)	0.071	-133	0.436	-133	1.292	-133	1.799
d (mm)	4.53		12.11		22.82		22.82
t_w (mm)	0.41		0.41		0.41		
t_s (µm)	20		25		35		
Regen. mat.	composite		phos. bronze		S.S.		
Porosity	0.30		0.55		0.60		
Mesh			250		325		
Par. dia(µm	183						
A_f (cm^2)	0.900		0.840		3.36		
D (mm)	10.70		10.34		20.68		
L (mm)	30.0		25		30		
V_{rg} (cm^3)	0.81		1.155		6.05		
V_{rg}/V_e	11.41		2.65		4.68		
P_r	1.700		1.735		1.798		1.889
P_1/P_0	0.2593		0.2687		0.2852		0.3077
$\Delta P/P_0$	0.00939		0.0165		0.0225		0.0200
T_r (K)	19.96		54.4		166.4		300.0
$\dot{m}_e$ (g/s)	0.81	-32	0.89	33	1.25	29	
$\dot{m}_c$ (g/s)	0.81	-32	1.43	18	2.40	11	
$\dot{P}V_{rg}/RT_r$(g/s	1.91	90	1.04	90	1.88	90	
$\dot{m}_h$ (g/s)	1.13	58	1.82	47	3.16	43	
$\dot{W}_c$ (W)	1.50		14.39		58.97		
$\dot{W}_e$ (W)	1.50		8.14		26.16		39
$\dot{Q}_{rm}$ (W)	1.52		7.75		25.42		
$\dot{Q}_r$ (W)	1.29		6.59		21.61		
$\dot{Q}_{reg}$ (W)	0.76		3.15		8.94		
$\dot{Q}_c$ (W)	0.12		0.08		2.28		
$\dot{Q}_{cs}$ (W)	0.02		0.18		2.64	(1.08,Ti)	
$\dot{Q}_{cd}$ (W)	0.00		0.02		0.27		
$\dot{Q}_g$ (W)	0.13		0.48		0.57		
$\dot{Q}_a$ (W)	0.07		0.51		6.22		
$\dot{Q}_{net}$ (W)	0.19		3.27		5.11	(6.67,Ti)	
$\dot{W}_h$ (W)	6.03		30.91		215.3		193
$\dot{W}_{h\Delta P}$ (W)	6.25		32.81		232.3		193
$\dot{W}_{co}$ (W)	60.7		90.8		120.2		
$\dot{W}_{co\,total}$ (W)			151.5		271.7		233
REGEN3.1	#922		#960		#957		
Factor	1.50		0.70		0.80		

Table 5b. Characteristics of aftercooler and compressor, 40 Hz, 1.5 MPa.

Parameter	Aftercooler 300 K	(Phase)	Conn. tube 320 K	(Phase)	Compressor 320 K	(Phase)	Electrical
V_{∞} (cm³)					17	-202	
d (mm)						(α=70°)	
t_w (mm)						(θ^*=22°)	
t_f (μm)						(θ=37°)	
Regen. mat.	copper						
Porosity							
Mesh							
Par. dia(μm							
A_c (cm²)							
D (mm)							
L (mm)							
V_{rg} (cm³)							
V_{rg}/V_s							
P_r	1.889				1.975		
P_1/P_0	0.3077				0.3277		
$\Delta P/P_0$	0.020						
T_r (K)	310				320		
$\dot{m}_a$ (g/s)							
$\dot{m}_c$ (g/s)	3.40	56					
PV_{rg}/RT_r(g/s	0.2*	90					
$\dot{m}_h$ (g/s)	3.53	58					
$\dot{W}_c$ (W)	193						
$\dot{W}_e$ (W)					3.2		3.8
$\dot{Q}_{rm}$ (W)							
$\dot{Q}_r$ (W)							
$\dot{Q}_{rmg}$ (W)							
$\dot{Q}_c$ (W)							
$\dot{Q}_{cl}$ (W)							
$\dot{Q}_{cd}$ (W)							
$\dot{Q}_g$ (W)							
$\dot{Q}_s$ (W)							
$\dot{Q}_{net}$ (W)							
$\dot{W}_h$ (W)	206				329		
$\dot{W}_{h\Delta P}$ (W)	219				329		387
$\dot{W}_{on}$ (W)							
$\dot{W}_{on\ total}$ (W)	(233)				(350)		(461)
REGEN3.1							
Factor							

Table 1. Characteristics of three cold stages, 20 Hz, 1.5 MPa, 6.0 mm stroke.

Parameter	3rd Stage 10 K, 0.15 W	(Phase) (deg)	2nd Stage 35 K, 2 W	(Phase) (deg)	1st Stage 80 K, 5 W	(Phase) (deg)	Warm end 300 K
V_e (cm^3)	0.107	-137	0.817	-137	4.76	-137	5.684
d (mm)	4.77		14.00		34.73		34.73
t_w (mm)	0.41		0.41		0.41		
t_s (μm)	23		30		40		
Regen. mat.	comp.		phos bronze		S.S.		
Porosity	0.30		0.55		0.643		
Mesh	-		325		325		
Par. dia(μm	183		-		-		
A_f (cm^2)	0.60		1.078		3.35		
D (mm)	(8.74)		11.72		20.65		
L (mm)	30.0		25.0		30.5		
V_{rg} (cm^3)	0.54		1.483		6.57		
V_{rg}/V_e	5.05		1.815		1.638		
P_r	1.700		1.721		1.750		1.832
P_1/P_0	0.2593		0.2649		0.2726		0.2937
$\Delta P/P_0$	0.00555		0.00770		0.0211		0.0200
T_r (K)	19.96		54.4		166.4		300.0
$\dot{m}_e$ (g/s)	0.54	-32	1.24	-30	2.09	-25	
$\dot{m}_r$ (g/s)	0.54	-32	1.27	-11	3.00	-11	
$\dot{P}V_{rg}/RT_r$ (g/s	0.64	90	0.65	90	0.98	90	
$\dot{m}_h$ (g/s)	0.43	65	1.12	17	2.91	7	
$\dot{W}_c$ (W)	0.99		11.84		71.06		-
$\dot{W}_e$ (W)	0.99		8.05		45.23		-59
$\dot{Q}_{rm}$ (W)	1.00		7.68		43.97		
$\dot{Q}_r$ (W)	0.85		6.53		37.37		
$\dot{Q}_{reg}$ (W)	0.35		2.11		11.76		
$\dot{Q}_c$ (W)	0.04		0.09		1.14		
$\dot{Q}_{cn}$ (W)	0.02		0.20		3.96	(1.60, Ti)	
$\dot{Q}_{cd}$ (W)	0.00		0.03		2.21		
$\dot{Q}_s$ (W)	0.13		0.43		1.85		
$\dot{Q}_e$ (W)	0.12		0.92		15.15		
$\dot{Q}_{net}$ (W)	0.19		3.41		5.08	(7.44, Ti)	
$\dot{W}_h$ (W)	3.71		25.10		256		217
$\dot{W}_{h\Delta P}$ (W)	3.79		25.83		276		217
$\dot{W}_m$ (W)	38.3		87.2		208.2		-
$\dot{W}_{m\ total}$ (W)	-		125.5		334		275
REGEN3.1	#923		#935		#941		
Factor	1.00		0.70		1.00		

Table 1b. Characteristics of aftercooler and compressor, 20 Hz, 1.5 MPa.

Parameter	Aftercooler 300 K	(Phase)	Conn. tube 320 K	(Phase)	Compressor 320 K	(Phase)	Electrical
V_{sw} (cm^3)					25	-223	
d (mm)						(α=86°)	
t_w (mm)						(θ^*=43°)	
t_g (μm)						(θ=58°)	
Regen. mat.	copper						
Porosity							
Mesh							
Par. dia(μm							
A_f (cm^2)							
D (mm)							
L (mm)							
V_{rg} (cm^3)							
V_{rg}/V_s							
P_r	1.832				1.914		
P_1/P_0	0.2937				0.3137		
$\Delta P/P_0$	0.020						
T_r (K)	310				320		
$\dot{m}_a$ (g/s)							
$\dot{m}_c$ (g/s)	2.63						
$\dot{P}V_{rg}/RT_r$(g/s							
$\dot{m}_h$ (g/s)	2.70						
$\dot{W}_c$ (W)	217						
$\dot{W}_e$ (W)					4.7		5.5
$\dot{Q}_{rm}$ (W)							
$\dot{Q}_r$ (W)							
$\dot{Q}_{reg}$ (W)							
$\dot{Q}_s$ (W)							
$\dot{Q}_{ct}$ (W)							
$\dot{Q}_{cd}$ (W)							
$\dot{Q}_g$ (W)							
$\dot{Q}_a$ (W)							
$\dot{Q}_{net}$ (W)							
$\dot{W}_h$ (W)	231				371		
$\dot{W}_{h\Delta P}$ (W)	247				371		436
$\dot{W}_{ro}$ (W)							
$\dot{W}_{m\ total}$ (W)	(275)				(413)		(485)
REGEN3.1							
Factor							

Table 2. Characteristics of cold stages, 20 Hz, 1.5 MPa, 6 mm stroke, longer 1st stage.

Parameter	3rd Stage 10 K, 0.15 W	(Phase) (deg)	2nd Stage 35 K, 2 W	(Phase) (deg)	1st Stage 80 K, 5 W	(Phase) (deg)	Warm end 300 K
V_e (cm^3)	0.107	-137	0.817	-137	4.76	-137	5.684
d (mm)	4.77		14.00		34.73		34.73
t_w (mm)	0.41		0.41		0.41		
t_g (μm)	23		30		40		
Regen. mat.	comp.		phos bronze		S.S.		
Porosity	0.30		0.55		0.60		
Mesh	-		325		250		
Par. dia(μm	183		-		-		
A_f (cm^2)	0.60		1.078		4.00		
D (mm)	(8.74)		11.72		22.57		
L (mm)	30.0		25.0		36.0		
V_{rg} (cm^3)	0.54		1.483		8.64		
V_{rg}/V_e	5.05		1.815		1.815		
P_r	1.700		1.721		1.750		1.815
P_1/P_0	0.2593		0.2649		0.2726		0.2894
$\Delta P/P_0$	0.00555		0.00770		0.0168		0.0200
T_r (K)	19.96		54.4		166.4		300.0
$\dot{m}_e$ (g/s)	0.54	-32	1.24	-30	2.09	-25	
$\dot{m}_c$ (g/s)	0.54	-32	1.27	-11	3.00	-11	
$\dot{P}V_{rg}/RT_r$(g/s	0.64	90	0.65	90	1.28	90	
$\dot{m}_h$ (g/s)	0.43	65	1.12	17	2.95	14	
$\dot{W}_c$ (W)	0.99		11.84		70.13		-
$\dot{W}_e$ (W)	0.99		8.05		44.30		-58
$\dot{Q}_{rm}$ (W)	1.00		7.68		42.89		
$\dot{Q}_r$ (W)	0.85		6.53		36.46		
$\dot{Q}_{reg}$ (W)	0.35		2.11		10.25		
$\dot{Q}_c$ (W)	0.04		0.09		1.61		
$\dot{Q}_{ct}$ (W)	0.02		0.20		3.36	(1.37, Ti)	
$\dot{Q}_{cd}$ (W)	0.00		0.03		1.67		
$\dot{Q}_g$ (W)	0.13		0.43		0.71		
$\dot{Q}_s$ (W)	0.12		0.92		12.84		
$\dot{Q}_{net}$ (W)	0.19		3.41		9.80	(11.79, Ti)	
$\dot{W}_h$ (W)	3.71		25.10		254		211
$\dot{W}_{h\Delta P}$ (W)	3.79		25.83		269		211
$\dot{W}_{co}$ (W)	37.8		85.9		201.0		-
$\dot{W}_{co\ total}$ (W)	-		123.7		325		267
REGEN3.1	#923		#935		#959		
Factor	1.00		0.70		1.00		

Table 2b. Characteristics of aftercooler and compressor, 20 Hz, 1.5 MPa.

Parameter	Aftercooler 300 K	(Phase)	Conn. tube 320 K	(Phase)	Compressor 320 K	(Phase)	Electrical
V_m (cm^3)					27	-218	
d (mm)						(α=81°)	
t_w (mm)						(θ*=38°)	
t_g (μm)						(θ=53°)	
Regen. mat.	copper						
Porosity							
Mesh							
Par. dia(μm							
A_f (cm^2)							
D (mm)							
L (mm)							
V_{rg} (cm^3)							
V_{rg}/V_e							
P_r	1.815				1.896		
P_1/P_0	0.2894				0.3094		
$\Delta P/P_0$	0.020						
T_r (K)	310				320		
$\dot{m}_e$ (g/s)							
$\dot{m}_c$ (g/s)	2.63						
$\dot{P}V_{rg}/RT_r$(g/s							
$\dot{m}_h$ (g/s)	2.70						
$\dot{W}_r$ (W)	211						
$\dot{W}_e$ (W)					4.7		5.5
$\dot{Q}_{rm}$ (W)							
$\dot{Q}_r$ (W)							
$\dot{Q}_{rez}$ (W)							
$\dot{Q}_c$ (W)							
$\dot{Q}_{cl}$ (W)							
$\dot{Q}_{cd}$ (W)							
$\dot{Q}_g$ (W)							
$\dot{Q}_c$ (W)							
$\dot{Q}_{net}$ (W)							
$\dot{W}_h$ (W)	225				362		
$\dot{W}_{h\Delta P}$ (W)	241				362		426
$\dot{W}_{co}$ (W)							
$\dot{W}_{co\ total}$ (W)	(267)				(401)		(471)
REGEN3.1							
Factor							

Table 3. Cold stages, 20 Hz, 1.5 MPa, 6 mm stroke, longer and smaller dia. 1st stage.

Parameter	3rd Stage 10 K, 0.15 W	(Phase) (deg)	2nd Stage 35 K, 2 W	(Phase) (deg)	1st Stage 80 K, 5 W	(Phase) (deg)	Warm end 300 K
V_s (cm^3)	0.107	-137	0.817	-137	4.28	-137	5.204
d (mm)	4.77		14.00		33.23		33.23
t_w (mm)	0.41		0.41		0.41		
t_g (μm)	23		30		40		
Regen. mat.	comp.		phos bronze		S.S.		
Porosity	0.30		0.55		0.60		
Mesh	-		325		250		
Par. dia(μm	183		-		-		
A_t (cm^2)	0.60		1.078		3.80		
D (mm)	(8.74)		11.72		22.00		
L (mm)	30.0		25.0		36.0		
V_{rg} (cm^3)	0.54		1.483		8.21		
V_{rg}/V_s	5.05		1.815		1.918		
P_r	1.700		1.721		1.750		1.815
P_1/P_0	0.2593		0.2649		0.2726		0.2894
$\Delta P/P_0$	0.00555		0.00770		0.0168		0.0200
T_r (K)	19.96		54.4		166.4		300.0
$\dot{m}_e$ (g/s)	0.54	-32	1.24	-30	1.92	-25	
$\dot{m}_c$ (g/s)	0.54	-32	1.27	-11	2.85	-11	
$\dot{P}V_{rg}/RT_r$(g/s	0.64	90	0.65	90	1.22	90	
$\dot{m}_h$ (g/s)	0.43	65	1.12	17	2.80	14	
$\dot{W}_r$ (W)	0.99		11.84		66.62		-
$\dot{W}_e$ (W)	0.99		8.05		40.79		-53
$\dot{Q}_{rm}$ (W)	1.00		7.68		39.49		
$\dot{Q}_r$ (W)	0.85		6.53		33.57		
$\dot{Q}_{reg}$ (W)	0.35		2.11		9.74		
$\dot{Q}_c$ (W)	0.04		0.09		1.53		
$\dot{Q}_{ct}$ (W)	0.02		0.20		3.22	(1.31, Ti)	
$\dot{Q}_{cd}$ (W)	0.00		0.03		1.49		
$\dot{Q}_g$ (W)	0.13		0.43		0.68		
$\dot{Q}_s$ (W)	0.12		0.92		12.29		
$\dot{Q}_{net}$ (W)	0.19		3.41		8.40	(10.31, Ti)	
$\dot{W}_h$ (W)	3.71		25.10		241		203
$\dot{W}_{h\Delta P}$ (W)	3.79		25.83		256		203
$\dot{W}_{cs}$ (W)	37.8		85.9		185.0		-
$\dot{W}_{cs\ total}$ (W)	-		123.7		309		256
REGEN3.1	#923		#935		#959		
Factor	1.00		0.70		0.95		

Table 3b. Characteristics of aftercooler and compressor, 20 Hz, 1.5 MPa.

Parameter	Aftercooler 300 K	(Phase)	Conn. tube 320 K	(Phase)	Compressor 320 K	(Phase)	Electrical
V_{co} (cm³)					26	-218	
d (mm)						(α=81°)	
t_w (mm)						(θ^*=38°)	
t_g (μm)						(θ=53°)	
Regen. mat.	copper						
Porosity							
Mesh							
Par. dia(μm							
A_t (cm²)							
D (mm)							
L (mm)							
V_{rg} (cm³)							
V_{rg}/V_s							
P_r	1.815				1.896		
P_1/P_0	0.2894				0.3094		
$\Delta P/P_0$	0.020						
T_r (K)	310				320		
$\dot{m}_a$ (g/s)							
$\dot{m}_t$ (g/s)	2.63						
$\dot{P}V_{rg}/RT_r$(g/s							
$\dot{m}_h$ (g/s)	2.70						
$\dot{W}_c$ (W)	203						
$\dot{W}_e$ (W)					3.2		3.7
$\dot{Q}_{rm}$ (W)							
$\dot{Q}_r$ (W)							
$\dot{Q}_{mg}$ (W)							
$\dot{Q}_c$ (W)							
$\dot{Q}_{ct}$ (W)							
$\dot{Q}_{cd}$ (W)							
$\dot{Q}_g$ (W)							
$\dot{Q}_e$ (W)							
$\dot{Q}_{net}$ (W)							
$\dot{W}_h$ (W)	217				347		
$\dot{W}_{h\Delta P}$ (W)	231				347		408
$\dot{W}_m$ (W)							
$\dot{W}_{co\ total}$ (W)	(256)				(384)		(452)
REGEN3.1							
Factor							

ALABAMA CRYOGENIC ENGINEERING (ACE)

REGENERATOR STUDIES

- Design a perforated plate/rare earth regenerator for the third stage:
  - Perform trade studies and optimizations for 3rd stage regenerator.
  - Based on gas flow characteristics from LMSC, design regenerator and perform thermodynamic analysis.
  - Provide recommendations for interfacing/ implementation of regenerator.
- Provide input to Phase 2 SOW including a cost quote to manufacture the regenerator.
- Provide recommendations for 1st and 2nd stage regenerators.

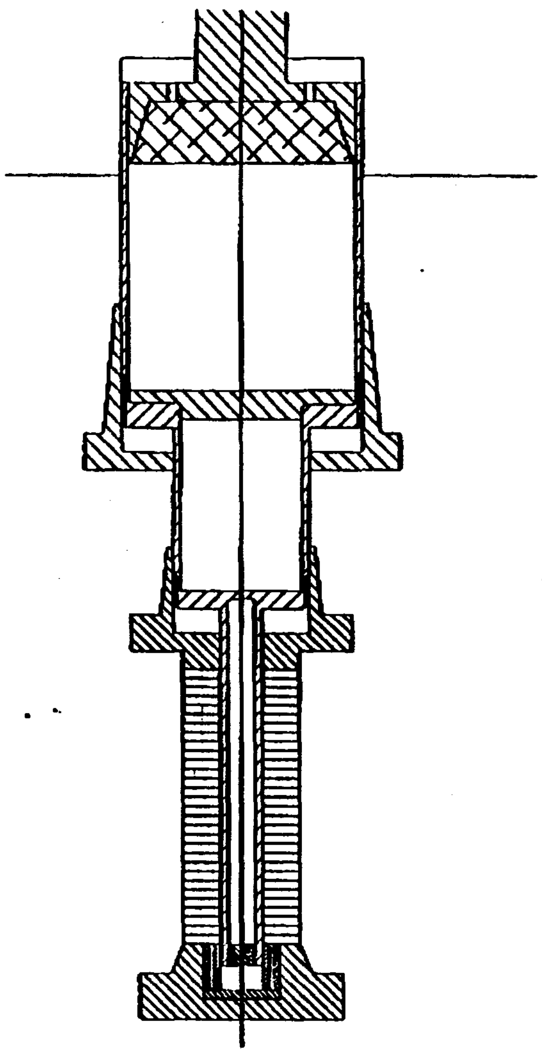
Lockheed R★DD

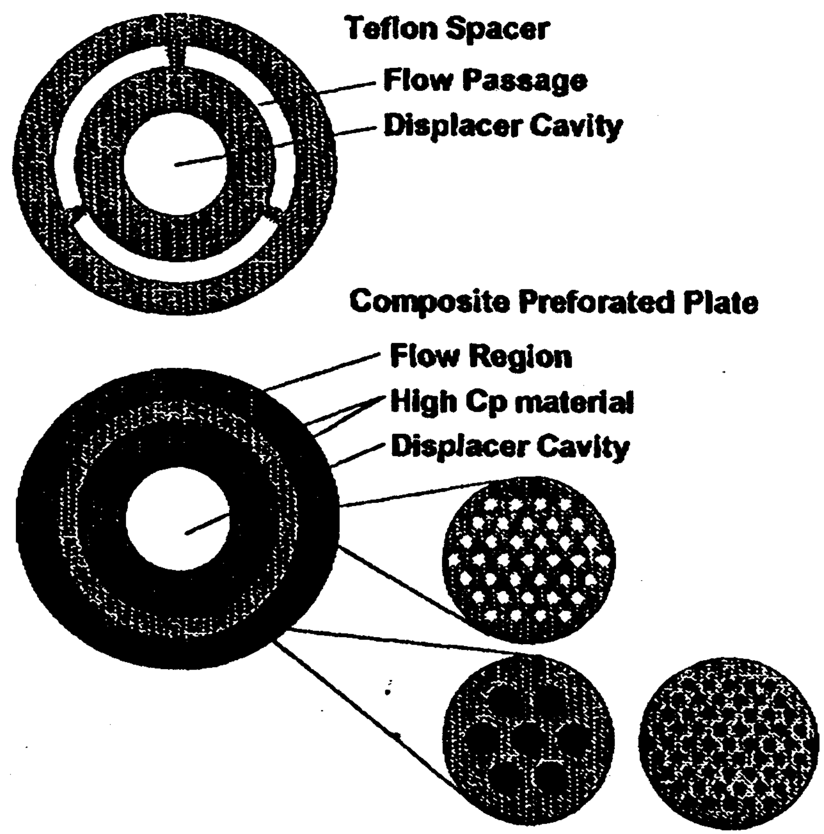
alabama cryogenic engineering, inc. ace

Regenerator Design

Composite Perforated Plate Concept

Air Force Phillips Laboratories Concept Design Review



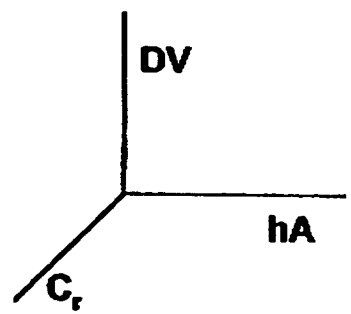


Geometry of high-Cp material is determined by thermal penetration effects.

Regenerator Design
Technical Approach

- Rerun baseline case -- provided by R. Radebaugh
  - validate installation of Regen 3.1
  - gain experience

- Move out each of the three trade axes
  - capacity ratio (C_r)
  - dead volume (DV)
  - heat transfer * Area product (hA)



- Develop consensus within the program on test cases for Phase 2

- Designs build on capabilities of composite perforated plates
  - nearly arbitrary C_r -- subject only to volume constraints
  - maximum hA per unit ΔP and DV
  - minimum DV for given hA and ΔP
  - all designs investigated <u>can be built</u>

Lockheed R★DD

alabama cryogenic engineering, inc. ace

Regenerator Design
Porosity and D_h Trades
Cooling Power

Air Force
Phillips Laboratories
Concept Design Review

Hydraulic Diameter (microns)	Net Cooling Power (Watts)				
	Porosity				
	0.10	0.15	0.20	0.25	0.40
10.0			no solution	0.91	0.71
14.1			0.91	0.85	0.63
20.0			0.78	0.72	0.51
28.3		no solution	0.59	0.50	
40.0	no solution	0.40	0.28		0.10

- **Use REGEN 3.1 for calculations**
  - **perforated plate system is modelled as axial tube flow**
  - **the matrix volume of the perforated plate system is equal to the packed sphere case**

- **Baseline case**
  - **100 micron Er_3Ni spheres with porosity = 38%**
  - **cooling power = 0.61 Watts**

Regenerator Design
Porosity and D_h Trades
Mass Flow

Hydraulic Diameter (microns)	MFLUX0 at Hot End (kg/sec) (x10^4)				
	Porosity				
	0.10	0.15	0.20	0.25	0.40
10.0			no solution	7.40	11.00
14.1			6.00	7.40	11.00
20.0			6.00	7.40	11.00
28.3		no solution	6.00	7.40	
40.0	no solution	5.70	6.00		11.00

- **Use REGEN 3.1 for calculations**
  - **perforated plate system is modelled as axial tube flow**
  - **the matrix volume of the perforated plate system is equal to the packed sphere case**

- **Baseline case**
  - **100 micron Er_3Ni spheres with porosity = 38%**
  - **mass flow = 11.0×10^{-4} kg/sec**

Regenerator Design Trade Studies

Baseline

Increase C_r holding hA and ΔP constant

- Insignificant improvement
- Penetration effects were tested and found to be insignificant

Reduce DV by reducing porosity (hydraulic diameter held constant)

- Significant increase in cooling power

Increase hA by reducing hydraulic diameter (porosity held constant)

- Significant increase in cooling power

Increase hA holding ΔP constant and increasing DV

- Significant decrease in cooling power

Regenerator Design
Porosity and D_h Trades
Results

- Changing hydraulic diameter, with a fixed porosity
  - smaller hydraulic diameter yields a larger number of holes
  - smaller hydraulic diameter increases the hA product, improving wall-fluid heat transfer
  - smaller hydraulic diameter increases the pressure drop. The pressure drop can increase to the point that REGEN 3.1 cannot find a solution

- Changing the porosity with a fixed hydraulic diameter
  - lower porosity yields fewer holes
  - lower porosity decreases dead volume and increases performance
  - lower porosity reduces the hA product
  - lower porosity increases the pressure drop. The pressure drop can increase to the point that REGEN 3.1 cannot find a solution.

Regenerator Design

Conclusions and Recommendations

- Significant improvements appear possible with perforated plates
  - reducing DV improves performance
  - increasing hA improves performance
- Regen 3.1 appears to give reasonable answers but there are some open questions -- further code improvements are recommended
  - performance appears insensitive to temperature gradient as though only the integrated C_r matters.
  - balancing and re-balancing mass flows at top and bottom of regenerator is very tedious, given long run times.
- Develop consensus within the program on regenerator designs for Phase 2
  - best course may be to move out each "axis" (DV,hA,C_r)
  - test cases will be selected in design task in Phase 2.
- Base designs on capabilities of composite perforated plates
  - nearly arbitrary C_r -- subject only to volume constraints
  - maximum hA per unit ΔP and DV
  - minimum DV for given HA and ΔP
  - all designs investigated <u>can be built</u>

MTI Linear-Motor-Driven Compressor

Presented by

Patrick Champagne

Lockheed Palo Alto Research Laboratory

February 1993

PROPOSED LMSC PHASE I PRESENTATION OUTLINE

- ☐ Design Specification
- ☐ Description of Compressor Concept
  - — Schematic Representation of Compressor
  - — Features and Benefits
  - — Helium Compression/Diaphragm Actuation
  - — Compressor Drive/Motor
  - — Pressure/Volume Compensating/Balancing
  - — Diaphragm Bellows Design
  - — Size Comparison (with Oxford)
  - — Compressor Cooling
  - — Inherent Unbalanced Forces
- ☐ Conceptual Layout for 10 K Application
  - — Moving Backiron Motor
  - — Weigh Table

PROPOSED LMSC PHASE I PRESENTATION OUTLINE

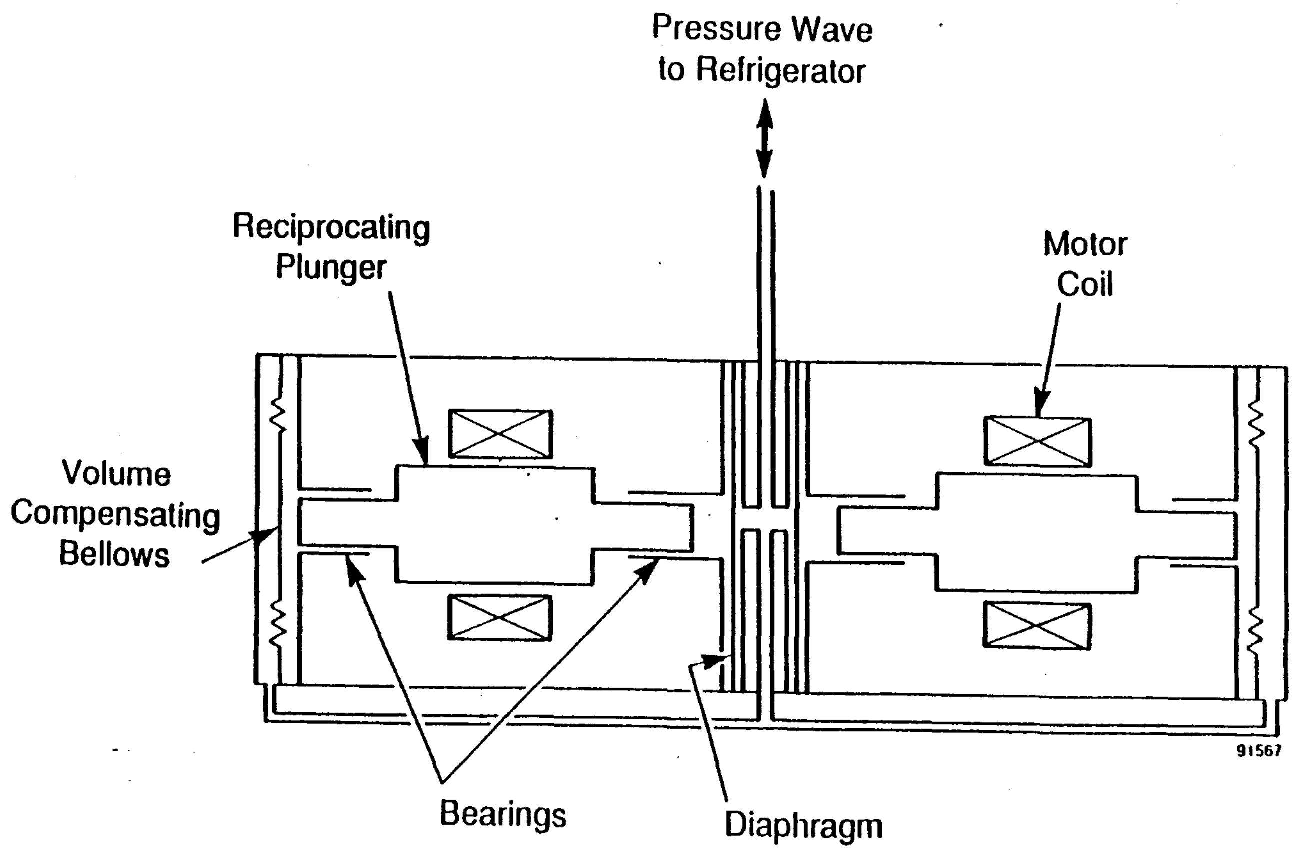
- ☐ Performance Summary
- ☐ Critical Issues
- ☐ Summary and Conclusions
- ☐ Proposed Phase II Activities

COMPRESSOR DESIGN PARAMETERS

- ❑ Initial fill pressure: 1.517 MPa (220 psia)
- ❑ Maximum pressure: 2.027 MPa (294 psia)
- ❑ Minimum pressure: 1.062 MPa (154 psia)
- ❑ Pressure swing (peak-to-peak): 0.965 MPa (140 psia)
- ❑ Total swept volume: 21.3 cc[(1)]
- ❑ Operating frequency: 40 Hz
- ❑ Piston position/pressure wave lag: 45°
- ❑ Minimum drive voltage: 22 V
- ❑ P-V power to gas: 512 W

(1) To Achieve 512 W of P-V power with the first harmonic of the pressure wave (0.965 MPa peak-to-peak and 45° lag), it is necessary to increase the swept volume to 23.8 cc)

CRYOCOOLER COMPRESSOR SCHEMATIC



DUAL-MODULE COMPRESSOR DESIGN

Features	Benefits
☐ Drive system hermetically isolated from helium environment	☐ No contamination of helium cycle by drive system
☐ No relative moving parts within helium cycle	☐ No requirement for dynamic seals
☐ Two compressor modules of identical design	☐ Minimizes development time and cost
☐ Each module has only one moving plunger — two per compressor which operate opposed on the same centerline	☐ No intrinsic unbalanced radial forces or unbalanced dynamic moments, simplified dynamic vibration control

DUAL-MODULE COMPRESSOR DESIGN

Features	Benefits
☐ Flooded oil environment for each compressor module	☐ Inherent zero-gravity design, uniform thermal management of compressor, no launch caging required
☐ Oil-lubricated, lightly loaded sleeve bearings with documented wear rate	☐ 100,000-hr life assured
☐ Linear reciprocating motor based on proven experience	☐ Assured performance
☐ All design tools, procedures, and data exist and validated	☐ No requirement for new technology needed for successful compressor development

METHOD OF HELIUM COMPRESSION

- ❑ Elastic deflection of metallic diaphragms provides positive displacement compression of helium in each compressor module
  - — Hermetic separation between helium gas and drive system hydraulic fluid
  - — Dynamic seals are eliminated within helium system

DIAPHRAGM ACTUATION

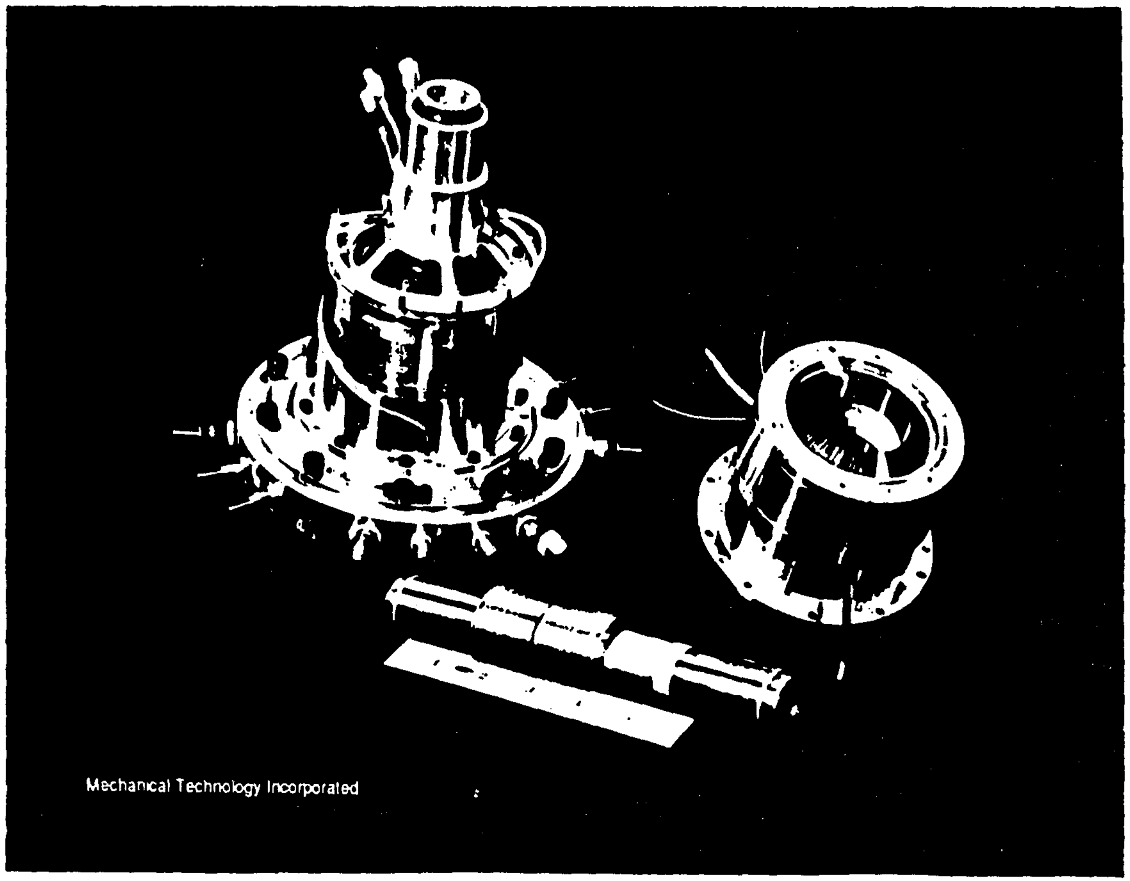
- Diaphragms are hydraulically actuated using an appropriate fluid
  - Differential pressures across diaphragms are small (3 to 4 psi) resulting in low diaphragm stress
  - Linear motors can be designed for long-stroke (~1.0 in.) operation for minimum size and weight
- Hydraulic pistons are mid-stroke ported
  - Replenishes hydraulic leakage through piston clearance seal

COMPRESSOR DRIVE

- ☐ Moving permanent-magnet linear motors (not moving coil motors)
  - — Minimizes magnetic air gap
  - — Eliminates flexing electrical conductors
- ☐ Oil-filled motor cavity
  - — Eliminates 0-g oil management problems
- ☐ Lightly loaded oil-lubricated sleeve bearings
  - — 100,000-hr life

LINEAR MOTOR FOR PHILLIPS LABORATORY

30 K Advanced Compressor (150 W, 40 Hz, 12-mm Stroke)



PRESSURE BALANCING/VOLUME COMPENSATING BELLOWS

- Each compressor drive module contains a metal bellows component to:
  - Maintain average hydraulic pressure essentially equal to average helium pressure in the refrigerators
  - Compensate for hydraulic fluid volume changes under all operating and nonoperating temperature conditions
  - Provide dynamic accommodation of changes in motor cavity volume due to piston displacement

DIAPHRAGM/BELLOWS DESIGN

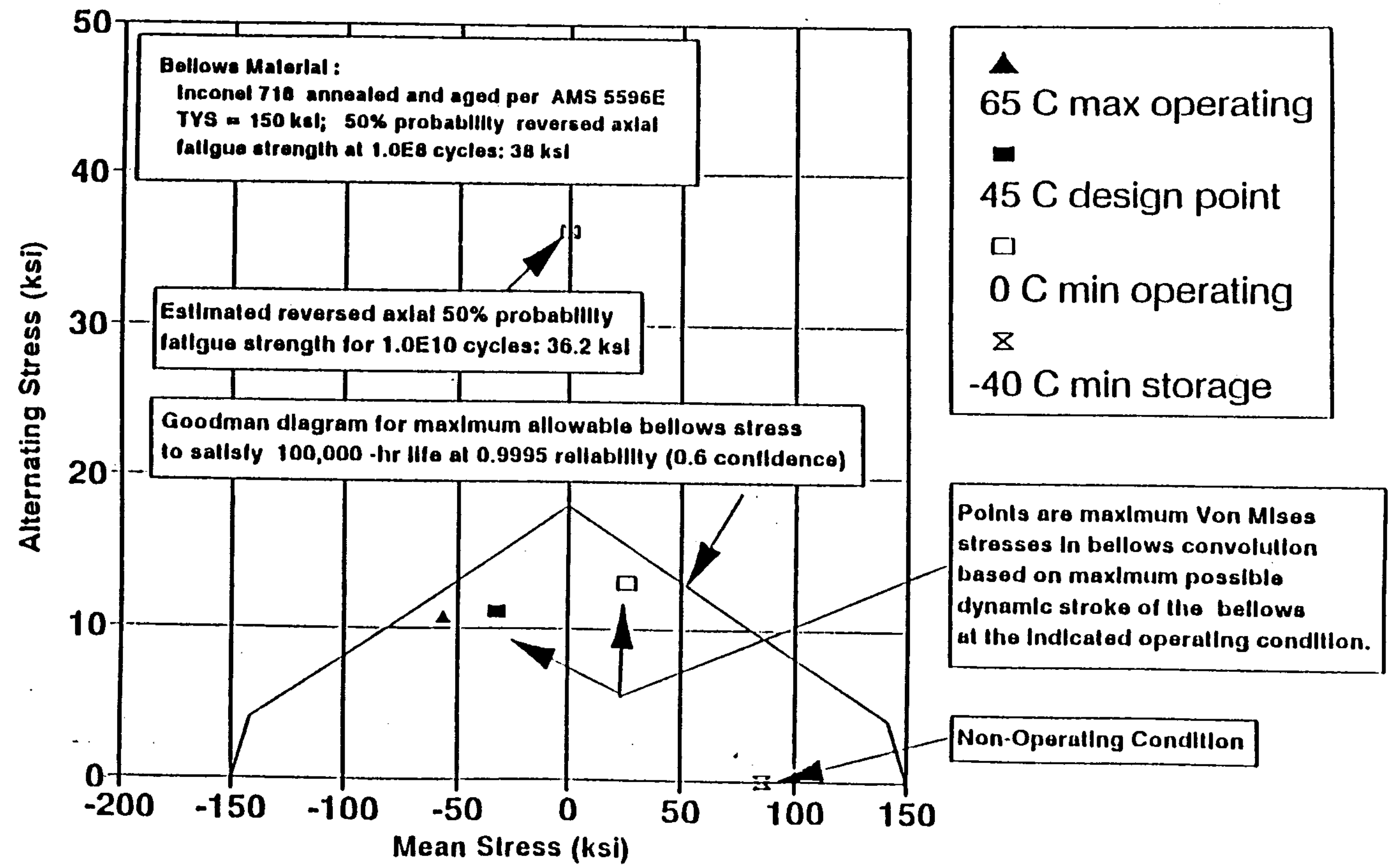
Diaphragms

- ☐ MTI design is based on statistical procedures for specified life, reliability, and confidence requirements
- ☐ MTI diaphragm tests support design approach

Bellows

- ☐ MTI design is based on statistical procedures for specified life, reliability, and confidence requirements
- ☐ Preliminary calculations indicate reliability levels for bellows will exceed those of diaphragms

BELLOWS STRESS AT FOUR OIL TEMPERATURES



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COMPRESSOR COOLING

- Four sources of energy dissipation (losses) within each compressor module must be thermally transferred to the spacecraft heat sink
  - Thermal hysteresis loss in the helium compression and bellows chambers
  - Motor electrical losses
  - Bearing friction losses
  - Fluid flow losses
- Oil-flooded motor will maintain uniform internal temperatures

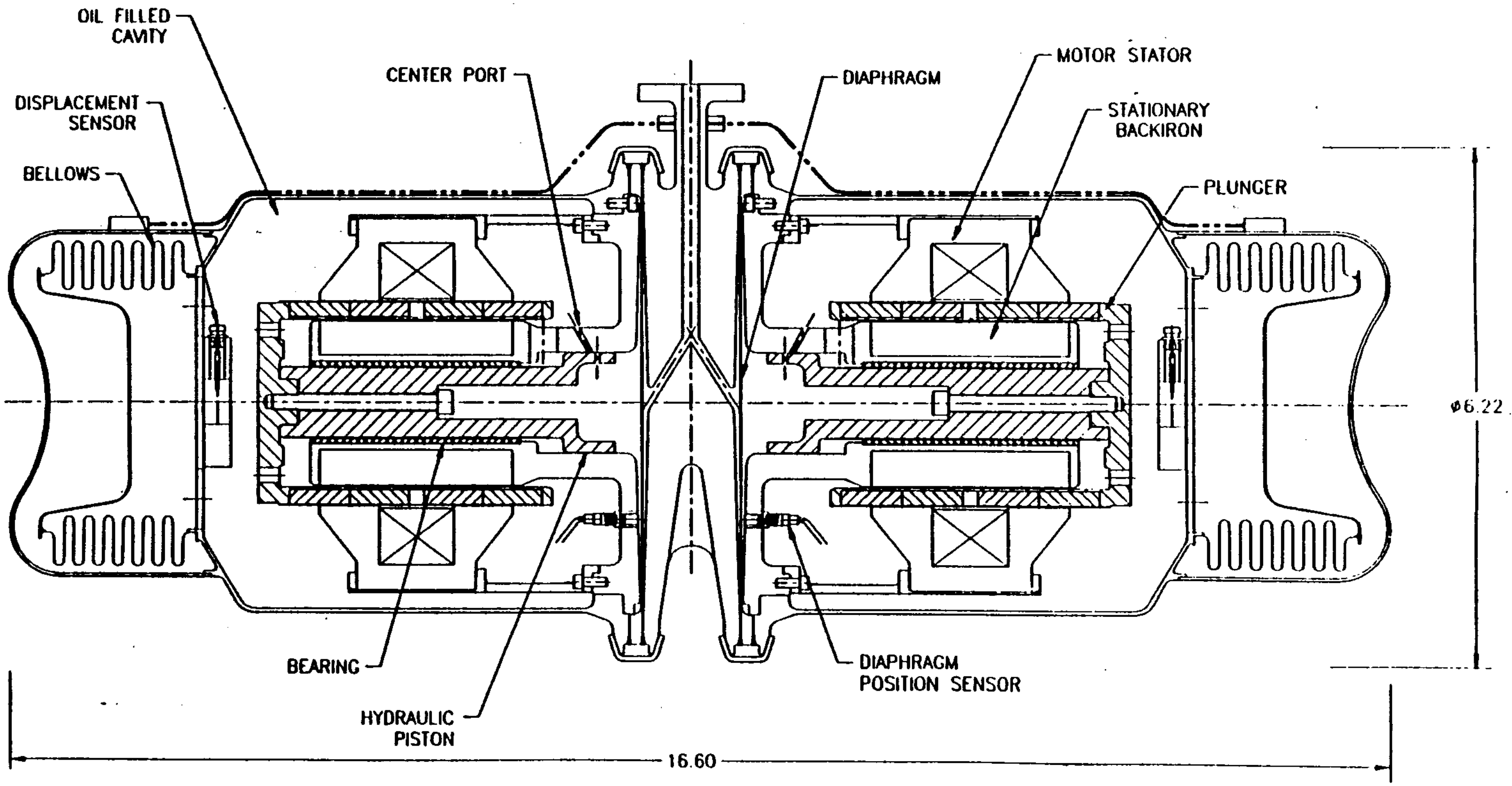
COMPRESSOR CONTROLS

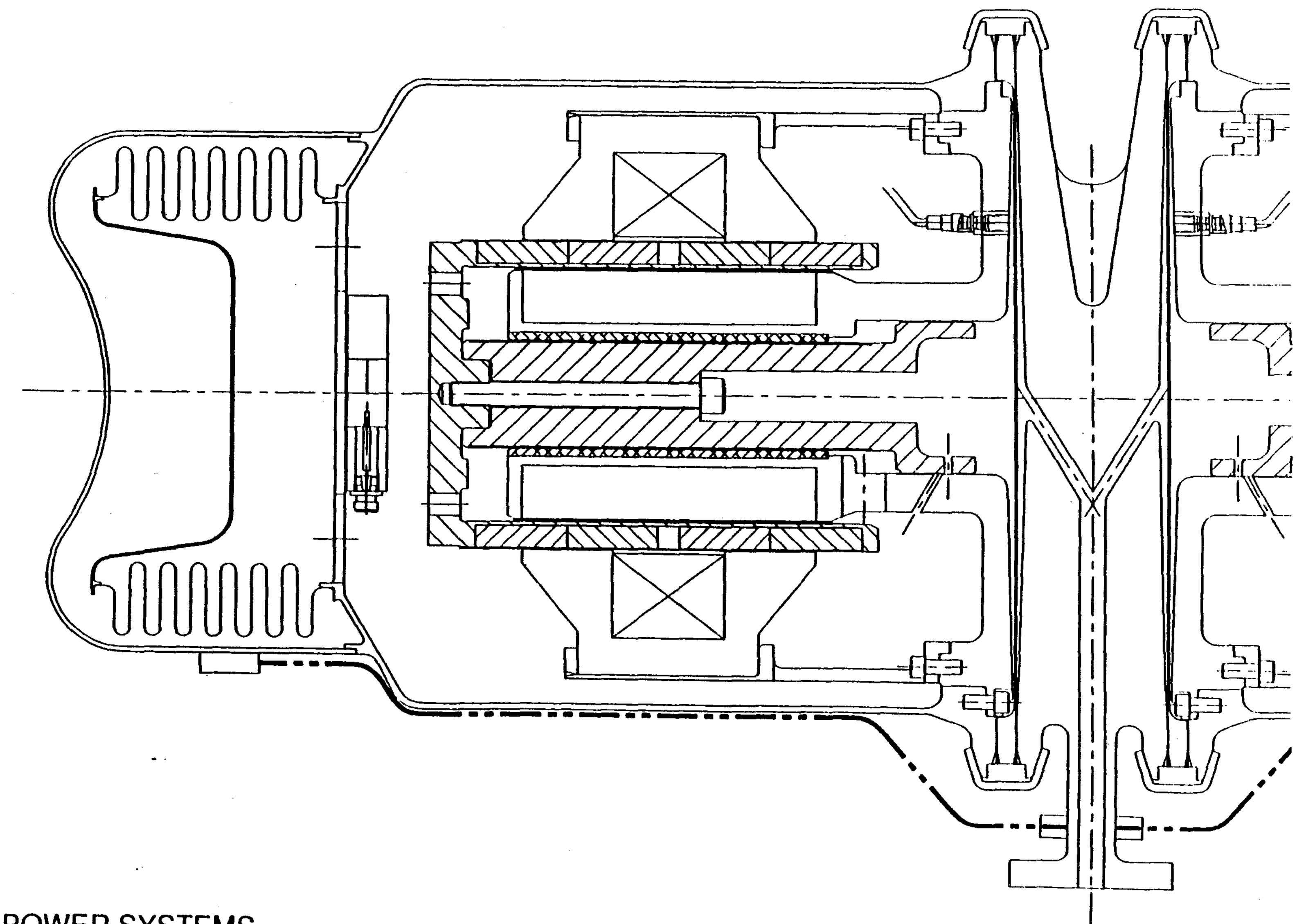
- ❑ Compressor controls are to be an integral element of an overall cryocooler controller
- ❑ Piston displacement sensors are used as the primary feedback signal
- ❑ Diaphragm displacement sensors are used to monitor absolute diaphragm position
- ❑ Case force transducers could provide additional information to the controller to further minimize vibration
- ❑ Additional monitoring of compressor pressures, temperatures, etc., can be provided

INHERENT UNBALANCED FORCES IN MTI'S COMPRESSOR

- ☐ Only axial forces in direction of plunger motion
- ☐ No intrinsic unbalanced moments or radial forces
- ☐ Only source of unbalanced moments or radial forces due to manufacturing and assembly tolerances
- ☐ Magnitude of reciprocating inertia force a function of linear motor type
  - — Moving backiron: 1.53 kg plunger mass; 532 N reciprocating inertia
  - — Stationary backiron: 0.76 kg plunger mass; 384 reciprocating inertia
- ☐ Assuming perfect plunger mass match and colinearity of CGs, a 0.1% stroke mismatch plus a 0.1° phase mismatch will produce a first harmonic unbalanced force of 0.546 N
- ☐ Active vibration control techniques required to reach specification limit of 0.05 N

16-mm STROKE, 40 Hz, 23.8 cc





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LOCKHEED COMPONENT WEIGHT BREAKDOWN

Reference Drawing 1061CSK-0006

DESCRIPTION	MATERIAL	QUANTITY	WEIGHT (Lbm) EACH	TOTAL
CENTER HOUSING	STN STEEL	1	4.295	4.295
DIAPHRAGM	17-4 PH	2	0.346	
INNER SUPPORT	ALUM ALLOY	2	0.850	
INNER STATOR	HYPERCO LAMS	2	1.680	
MOTOR	HYPERCO LAMS	2		
(COPPER AND IRON)	SQUARE WIRE	2	4.220	
			6.750	13.500
(RECIPROCATING MASS)				
*PLUNGER	ALUM ALLOY	2	0.199	
*CARRIER BODY	ALUM ALLOY	2	0.137	
*MTG RING	ALUM ALLOY	2	0.058	
*MAGNETS AND WRAP		2	0.918	
*MAKE-UP		2	0.369	
			1.682	3.364
(PRESSURE VESSEL)				
*MAIN BODY	STN STEEL	2	1.946	
*SHELL END	STN STEEL	2	0.446	
*BELLOWS	INCONEL 718	2	0.203	
*BELLOWS CAP	STN STEEL	2	0.079	
*CLAMP	STN STEEL	2	0.332	
			3.006	6.012
(MOTOR FRAME)				
*MTG RING	ALUM ALLOY	2	0.056	
*SUPPORT CYLINDER	ALUM ALLOY	2	0.139	
*WEBS (x5) 0.06" THK	ALUM ALLOY	2	0.198	
			0.393	0.786
(CAPACITANCE PROBE)				
*CENTER TIP	ALUM ALLOY	2	0.007	
*GUARD	ALUM ALLOY	2	0.053	
			0.060	0.120
OIL		2	1.989	3.978
				32.747

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PERFORMANCE OF MTI'S DUAL-OPPOSED COMPRESSOR

- ☐ When operating at the specified design-point conditions, the predicted performance of MTI's dual-opposed compressor using stationary-backiron motors is as follows:
  - — Cylinder pumping power to drive cryocooler: 512.0 W
  - — Gas-to-wall cyclic heat transfer loss in cylinder: 50.6 W
  - — Total compression cylinder P-V power: 562.6 W
  - — Motor efficiency: 86.1%
  - — Overall compressor efficiency (excluding sensor and power electronics, but including compressor hydraulic losses): 75.3%
  - — Compressor input power at motor terminals: 680.0 W
  - — Compressor operating hours for 0.025-mm (0.001-in.) of bearing wear: 117,7700

CRITICAL ISSUES

- ☐ Long-term dc stability of diaphragm and plunger sensors
- ☐ Possible compressor/control system instabilities
- ☐ Excessive higher order vibration harmonics

CRITICAL ISSUES

Long-Term dc Stability of Diaphragm and Plunger Sensors

- ☐ MTI has developed and demonstrated a capacitance sensing system for the ERIS program whose goal was less than 0.1% FS drift over a 15-yr period
- ☐ Demonstrated performance was less than 0.02% per year over a temperature range of 20 to 65°C
- ☐ Optical sensors on the helium side utilizing digital processing techniques have been suggested as a possibly simpler and less expensive approach

CRITICAL ISSUES

Possible Compressor/Control System Instabilities

- ☐ System instability is not considered to be a "show stopper" and stable operation is expected to be demonstrated during actual compressor testing in the very near future
- ☐ If instabilities are experienced, it is expected that a combination of development testing and simulation model analysis will produce a viable solution

CRITICAL ISSUES

Excessive Higher Order Vibration Harmonics

- ☐ Possibly caused by diaphragm and motor force nonlinearities
- ☐ Can be reduced by derating motor and diaphragm design at the expense of increased compressor weight
- ☐ Expect that existing electronic vibration control techniques are directly applicable to diaphragm compressors
- ☐ Results of eminent compressor test program will give an initial appraisal of the magnitude of the higher harmonic vibration content

SUMMARY

- ❑ MTI's compressor design using aluminum and stainless steel construction materials is highly feasible and within the bounds of common fabrication and welding procedures. Linear motor design requirements are well within the envelope of MTI's demonstrated experience.

- ❑ Compressor weight can be reduced by using beryllium in place of some of the stainless steel and aluminum parts. However, procedures for brazing beryllium to stainless steel would need to be qualified with regard to hermeticity and strength of the pressure-containment braze joints.

SUMMARY

- ☐ Active vibration suppression techniques will be required to achieve the specified residual dynamic force levels. MTI believes that proven suppression techniques can be applied to our compressor, but this has not yet been demonstrated.

- ☐ The intrinsic cleanliness and hermeticity of the helium side of MTI's compressor, combined with the simplicity and ruggedness of the lightly loaded, oil-lubricated motor bearings, provides a high degree of assurance that our compressor can achieve the required levels of life and reliability.

PROPOSED PHASE II ACTIVITIES

Critical Component Demonstration and Preliminary Design

Task 1.0: Preliminary Design Layout

- ☐ Prepare preliminary design layout of the compressor design selected during Phase I with emphasis on:
  - — Minimization of compressor weight
  - — Design of hermetic and structural joints
  - — Design of plunger displacement probe
  - — Integration of pressure balance line into compressor structure
  - — Compressor mounting/interfacing design
  - — Compressor cooling

Task 2.0 Design Optimization

- ☐ Optimize the compressor design with respect to frequency, pressure level and amplitude, displacement, etc. so as to minimize compressor weight, transmitted vibration, and input power

PROPOSED PHASE II ACTIVITIES

Critical Component Demonstration and Preliminary Design

Task 3.0: Component and System Sizing

- ☐ Finalize the compressor assembly layout drawing and size all compressor components based upon the work accomplished under Tasks 1.0 and 2.0. This layout will form the basis of the detail design work to be accomplished under Phase III which may follow. The component designs (motors, diaphragms, bellows, basic power control system approach) will be conceptually the same as current MTI designs but will be sized and stressed to levels consistent with the subject program requirements.

Task 4.0: Update Performance Estimates

- ☐ Update previous performance estimates based upon the design prepared under Task 3.0.

FLEXURE BEARING COMPRESSOR
Operation

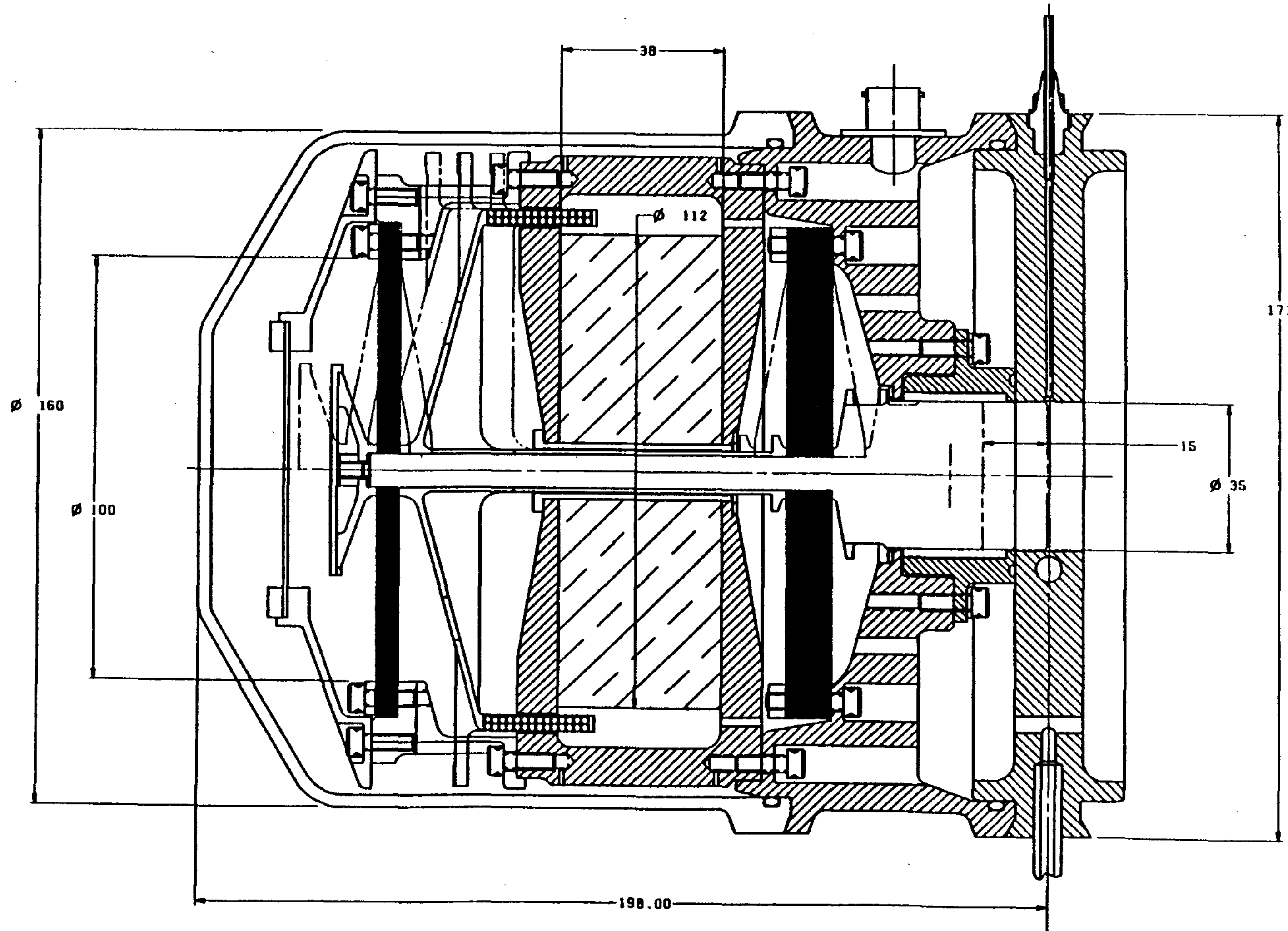
- Spiral-flexure diaphragm springs produce nonsliding linear motion
- Piston clearance seals eliminate wear
- Direct drive linear motor uses no contacting moving parts
- Position sensor provides precision feedback for control loop

Lockheed

R&DD

FLEXURE BEARING COMPRESSOR
Layout

Air Force
Phillips Laboratories
10K CoDR



PJC 4mar93

FLEXURE BEARING COMPRESSOR
Advantages

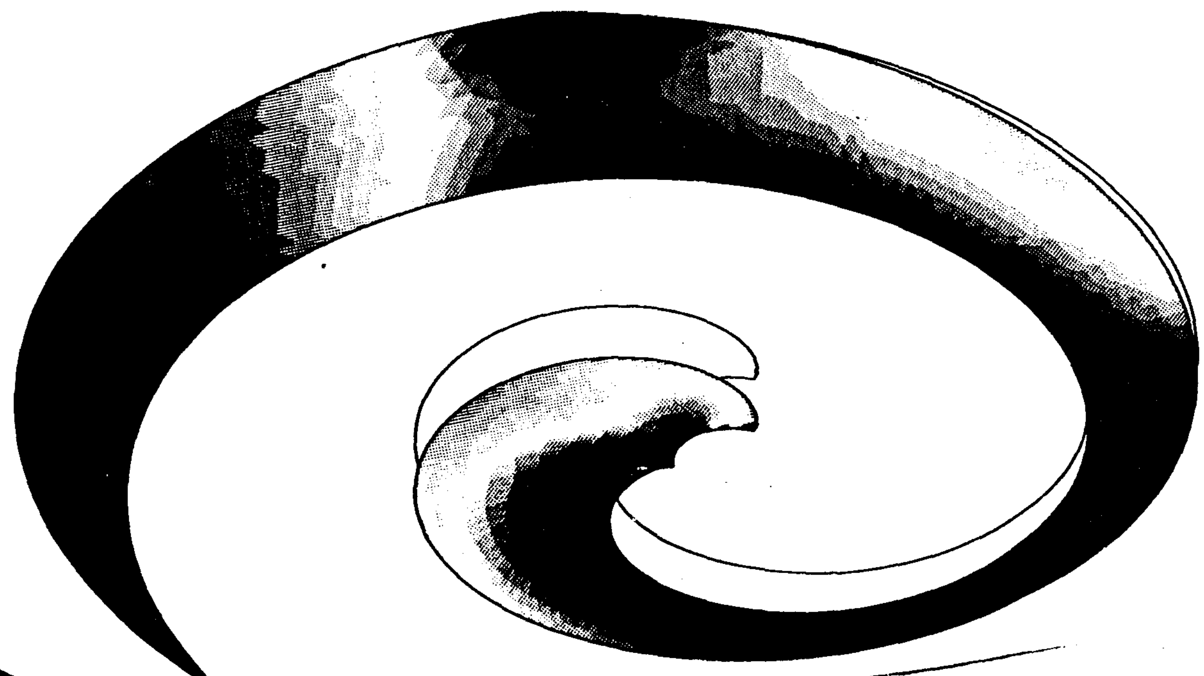
- Traditional "Oxford" approach: no contacting moving parts
- Simplified mechanical system: only one moving component
- Stable, all-metallic mechanism
- Proven technology
- Scaled up from existing hardware

Lockheed
R&DD

FLEXURE BEARING COMPRESSOR
Spring Stress Analysis

Air Force
Phillips Laboratories
10K CoDR

LMSC (0.125,420) Spiral, Stainless Steel, (Ro,t) = (2.0,0.015)
Effective Stress (in N/mm^2) @ 7.6 mm Extension, Max. = 36 Ksi



DIAL L3D3

EDGE PLOT

MIN 0.117E-04
1 0.117E+02
2 [illegible]
5 [illegible]
6 0.705E+02
7 0.822E+02
8 0.940E+02
9 0.106E+03
0 0.117E+03
A 0.129E+03
B 0.141E+03
C 0.153E+03
D 0.164E+03
E 0.176E+03
F 0.188E+03
G 0.200E+03
H 0.211E+03
I 0.223E+03
J 0.235E+03
MAX 0.247E+03

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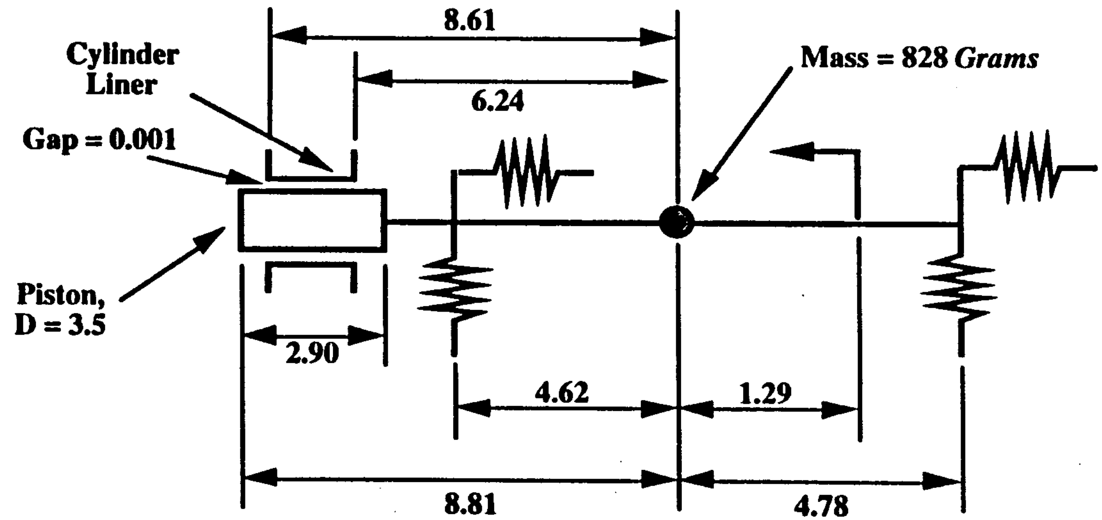
FLEXURE BEARING COMPRESSOR
Spring Configuration Study

Air Force
Phillips Laboratories
10K CoDR

- 10K Compressor dynamics model (*dimensions in centimeters*):



- LMSC (0.125,420°) spiral springs, stainless steel, 4 *in.* outer diameter, 0.015 *in.* thickness
- Operating conditions: 220 *psi* fill pressure, maximum stroke, 40 *Hz* operating frequency
- Study included forces and moments generated within the clearance seal during operation

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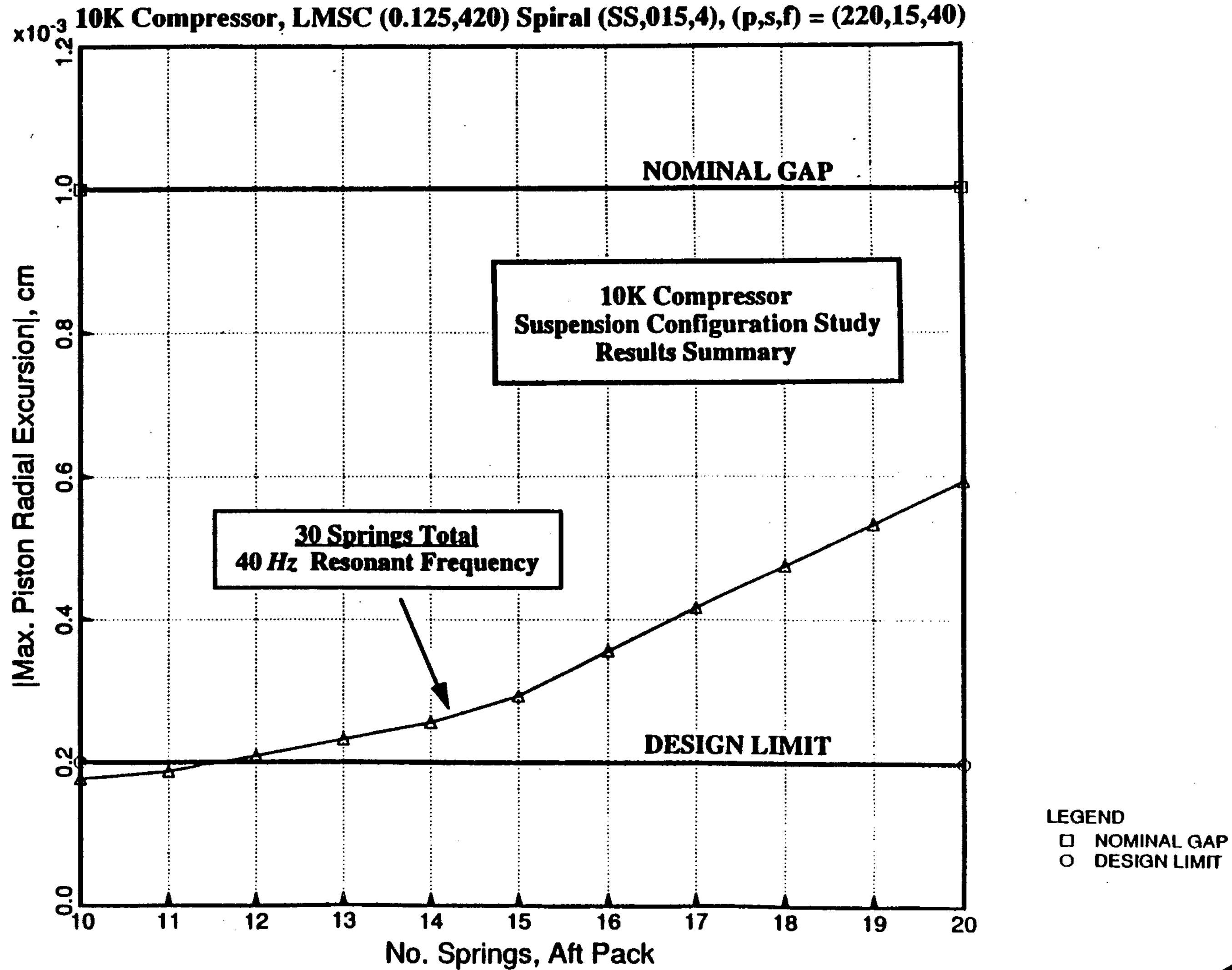
FLEXURE BEARING COMPRESSOR
Spring Configuraton Results

Air Force
Phillips Laboratories
10K CoDR



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FLEXURE BEARING COMPRESSOR
Spring Design Summary

Air Force
Phillips Laboratories
10K CoDR

- The LMSC (0.125,420°) spiral spring, stainless steel, with an an outer diameter of 4 *in.* and a thickness of 0.015 *in.* is a good choice for the 10K Compressor

- Spring stresses @ max. stroke are low
  -- Max. effective stress = 36 *Ksi*

- A resonant frequency of 40 *Hz* is achieved with 30 springs, total

- With a partitioning of 20/10 springs in the forward/aft spring packs, the maximum piston radial excursion @ max. stroke = 17% of nominal clearance

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FLEXURE BEARING COMPRESSOR
Linear Motor Drive

Air Force
Phillips Laboratories
10K CoDR

- Permanent magnet, moving coil
- Stable, Samarium-Colbalt magnet
- Low moving mass
- Linear force constant over stroke
- Minimum radial reaction forces
- Magnetic clamping of pole pieces

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FLEXURE BEARING COMPRESSOR
Linear Motor Parameters

Air Force
Phillips Laboratories
10K CoDR

Per module motor:

- Operation: 40 Hz
- Maximum force: 90 lbf
- Stroke: 15 mm
- Design voltage: 22
- Average current: 17 amp
- Output power: 252 watts

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R&DD

FLEXURE BEARING COMPRESSOR
Weight Break Down

Air Force
Phillips Laboratories
10K CoDR

Component	Material	Weight (per module)
moving mass		
coil carrier	stainless steel	0.38 lb
coil wire	copper	0.52 lb
piston	alum alloy	0.23 lb
shaft	stainless steel	0.09 lb
target plate	alum alloy	0.03 lb
front spring pack	stainless steel	1.35 lb
rear spring pack	stainless steel	0.67 lb
linear motor		
magnet	rare earth	6.76 lb
pole	steel	1.44 lb
yoke	steel	5.88 lb
structure		
front housing	alum alloy	3.52 lb
rear cover	alum alloy	1.57 lb
center housing	alum alloy	1.08 lb
rear spring mount	alum alloy	1.17 lb
	TOTAL	24.7 lb per module

PJC 4mar93

FLEXURE BEARING COMPRESSOR
Critial Issues

- Coil outgassing contamination
  - potting material
  - aspect ratio (no of layers)
- Vibration cancellation
  - large moving mass
  - tolerance control of larger parts
- Heat transfer
  - from compressed gas
  - from motor coil

Lockheed R&DD

FLEXURE BEARING COMPRESSOR
Summary

Air Force
Phillips Laboratories
10K CoDR

- Meets weight, size, and power goals
- Low-risk scaling of existing technology
- Experienced vibration control issues
- Mature flexure design and analysis
- Known material selection criteria

PJC 4mar93

MANUFACTURING and ALIGNMENT

ALIGNMENT TEST PROGRAM

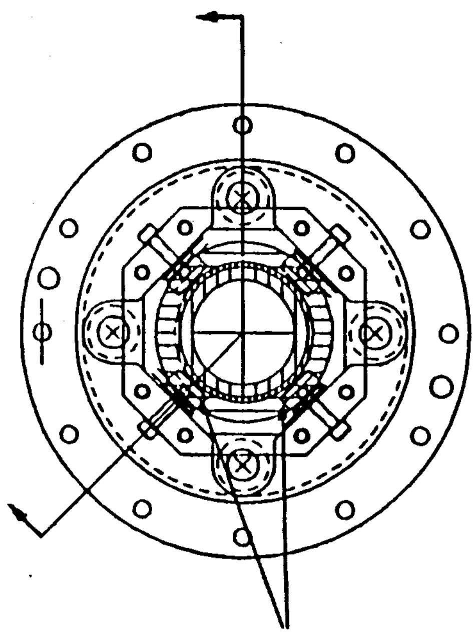
- QUANTIFY "TYPICAL BUILD STANDARD"
  - AVIONICS UNIT USED AS TEST BED
  - TARGET PLATE XY-MOTION -VS- Z POSITION
  - FUNCTION OF FREQUENCY, PRESSURE
  - DETERMINE EFFECT OF CONNECTOR STRIPS
- RE-ALIGN MOVING MASS
  - ANGULARITY
  - CENTERING
- REPEAT MOTION CHARACTERIZATION TESTS AS ABOVE
  - PROCESS DIRECTLY APPLICABLE TO 80K
  - CENTERING TO BE USED ON SCRS PROGRAM FIRST

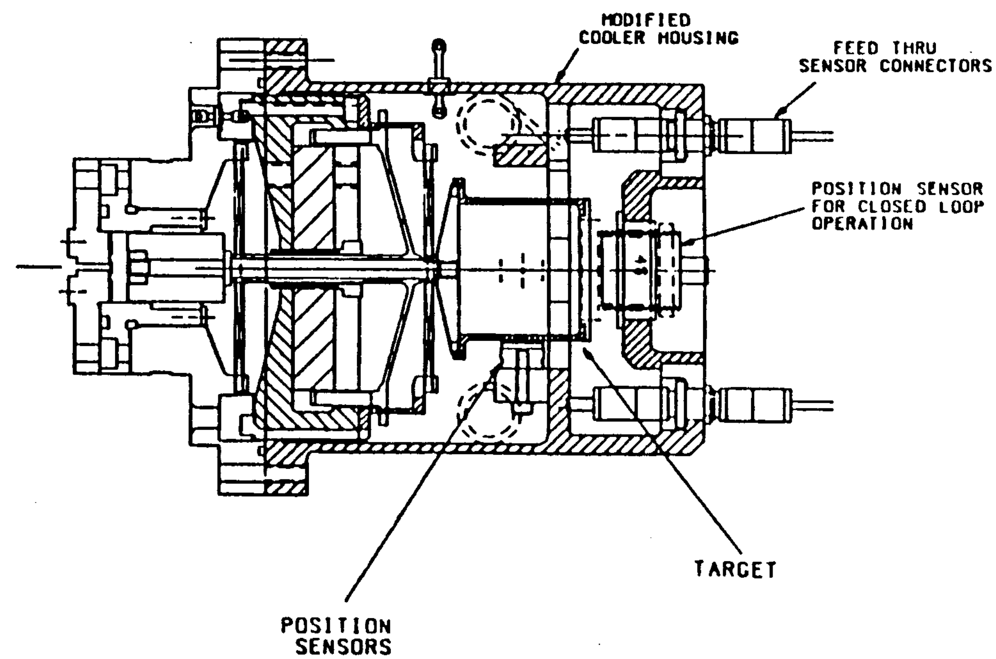
Lockheed
Lucas Aerospace

DYNAMIC EXCURSION TEST HARDWARE

P/059824

NASA
80K CDR





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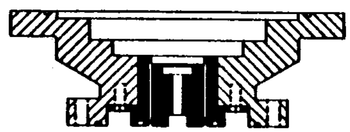
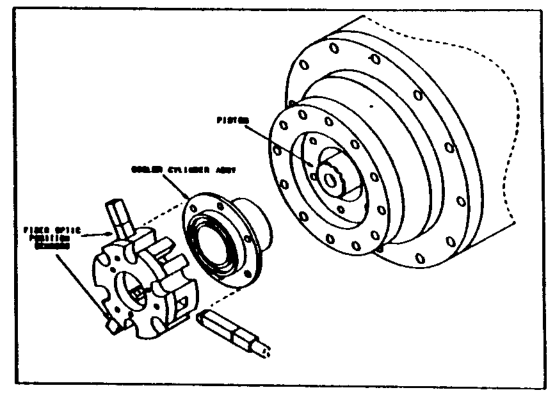
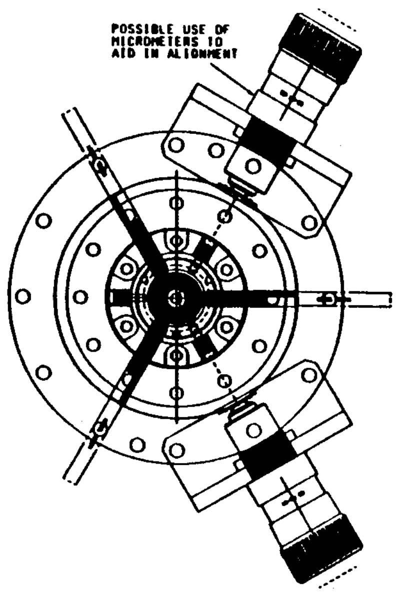
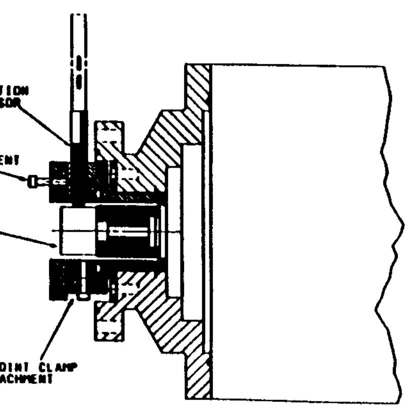
PISTON/LINER CENTERING DEVICE

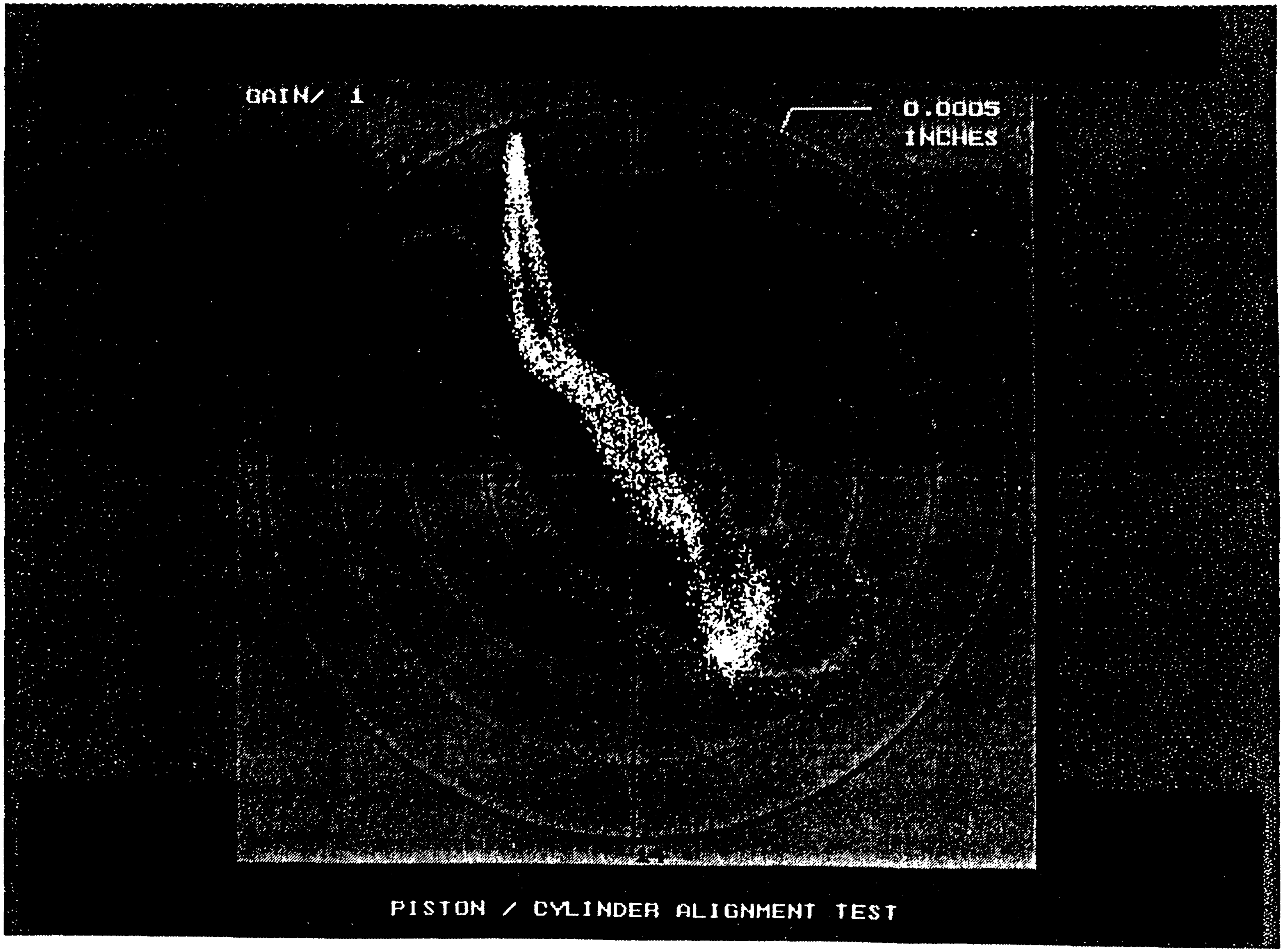
P/059824
NASA
80K CDR



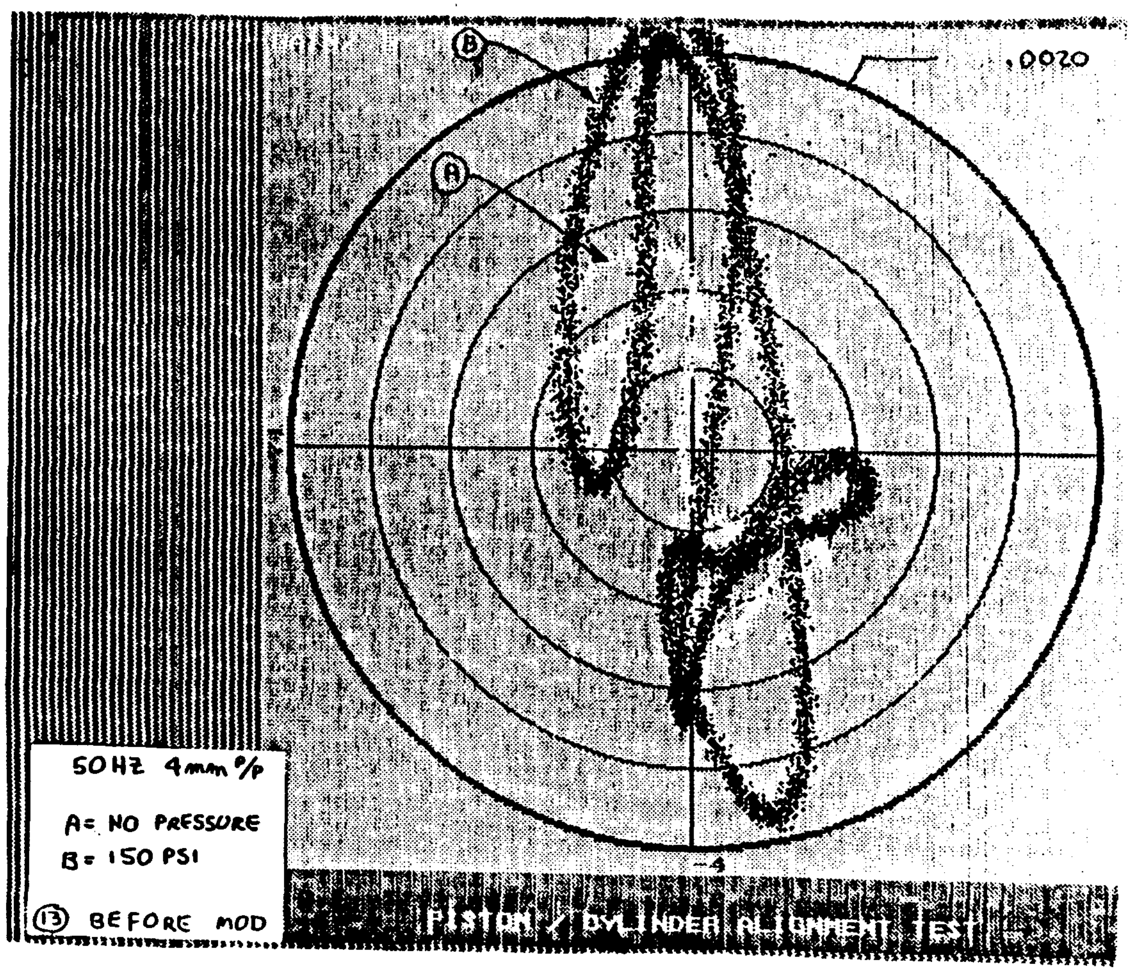







GAIN/ 1
0.0005
INCHES
PISTON / CYLINDER ALIGNMENT TEST

EFFECT OF PRESSURE ON PISTON MOTION



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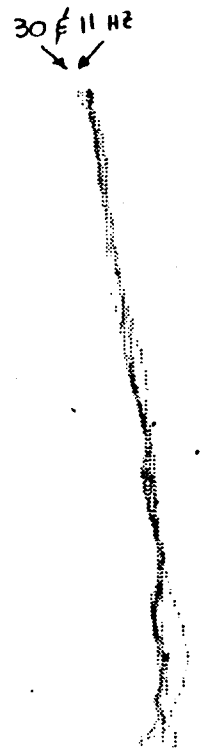
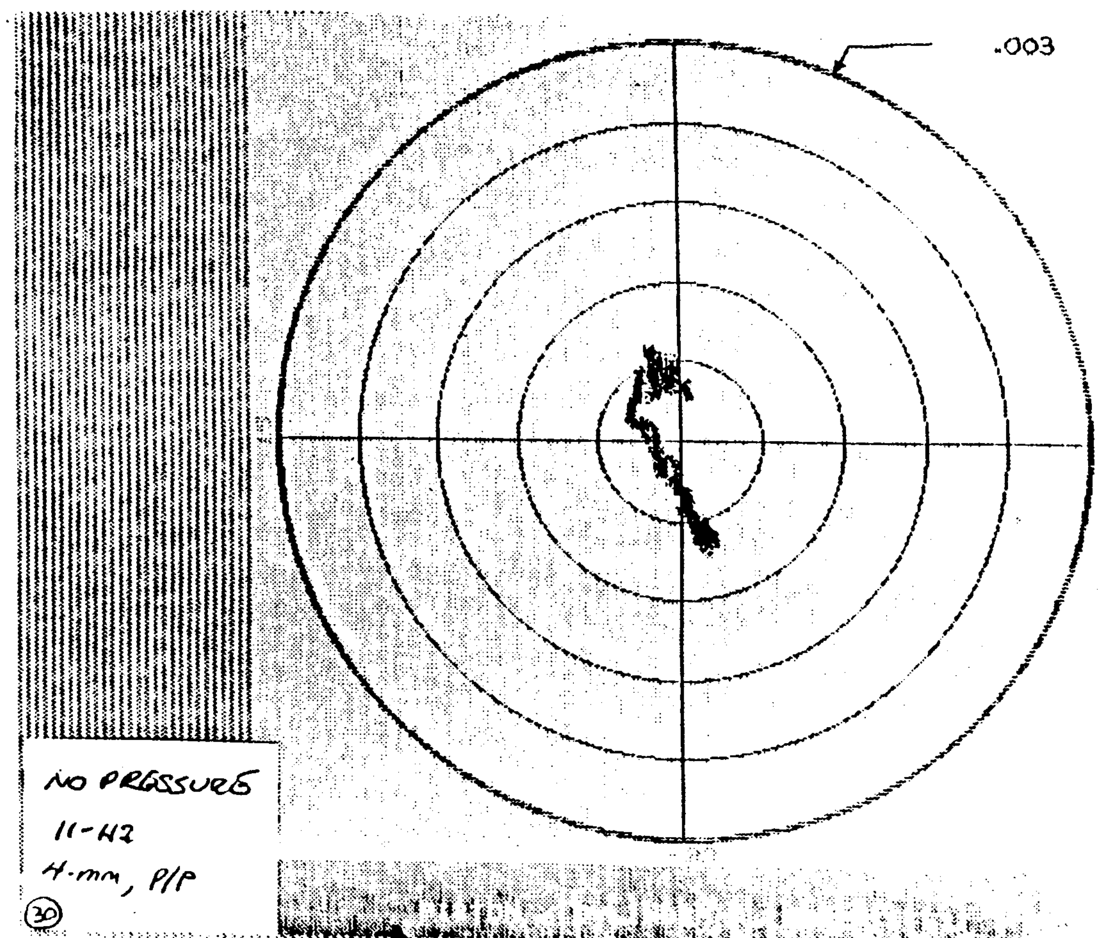
EFFECT OF FREQUENCY ON PISTON MOTION

P/059824

NASA
80K CDR

DEC023 = 11 Hz
DEC026 = 30 Hz





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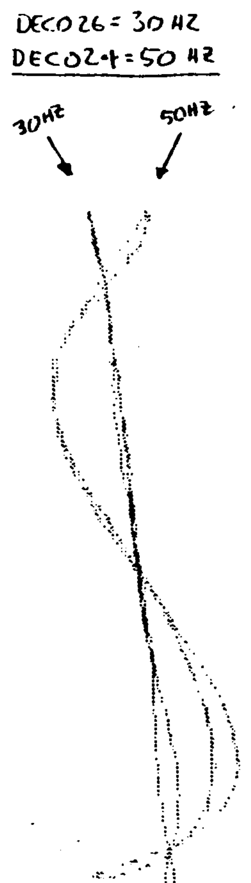
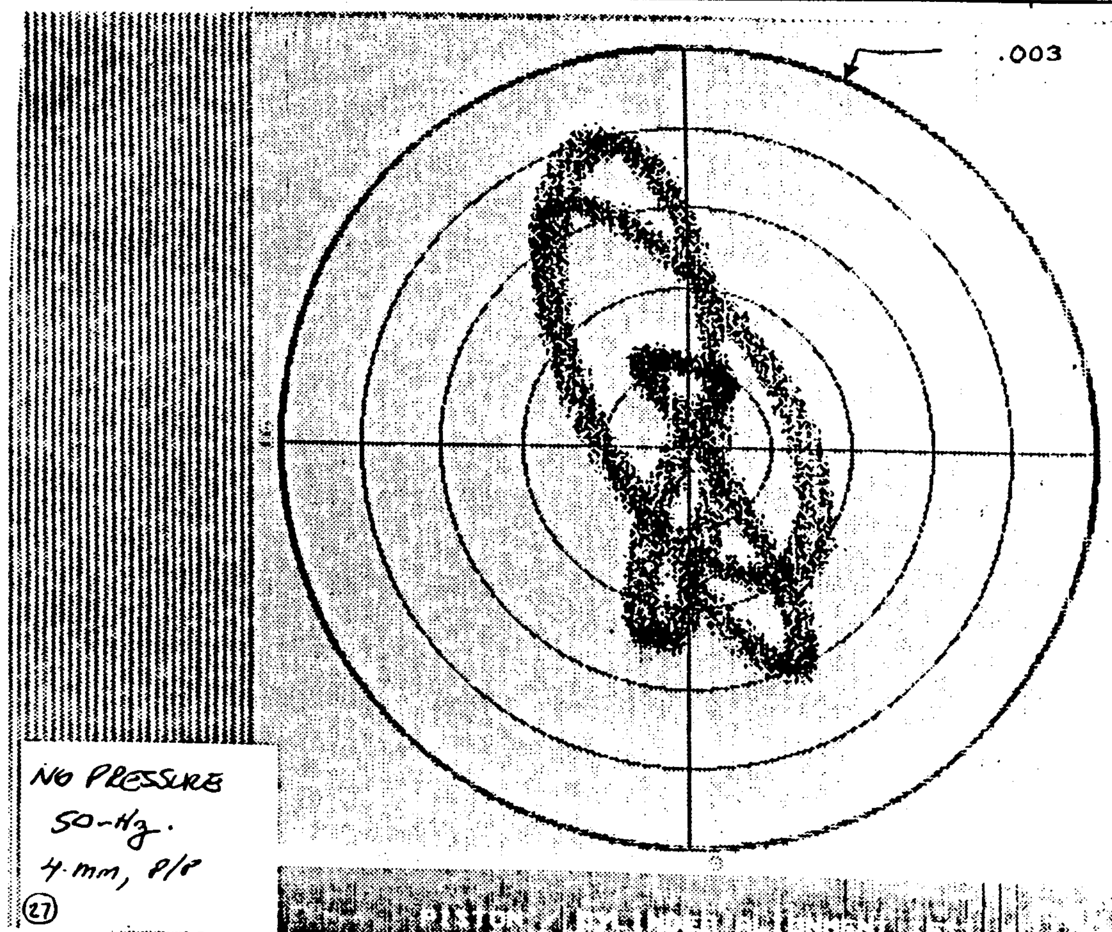
EFFECT OF FREQUENCY ON PISTON MOTION

NASA

80K CDR





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ALIGNMENT PROGRAM SUMMARY

P/059824
NASA
80K CDR

- A TECHNIQUE FOR MEASURING THE MOTION OF THE MOVING MASS HAS BEEN DEMONSTRATED IN THE LABORATORY
    - QUANTIFIES MAGNITUDE OF MOTION
    - ALLOWS EFFECTS OF ALIGNMENT EFFORT TO BE SEEN
    - CURRENT SET-UP LIMITED BY SPRING ARM MOVEMENT @ 50-HZ
    - TESTING CONTINUES TO DETERMINE SYSTEM SENSITIVITIES

- 80K BASELINE COMPATABLE WITH ALIGNMENT SCHEME
    - FIRST USE OF CENTERING DEVICE TO BE IMPLEMENTED ON SCRS BUILD

FINAL ASSEMBLY

NOTE:

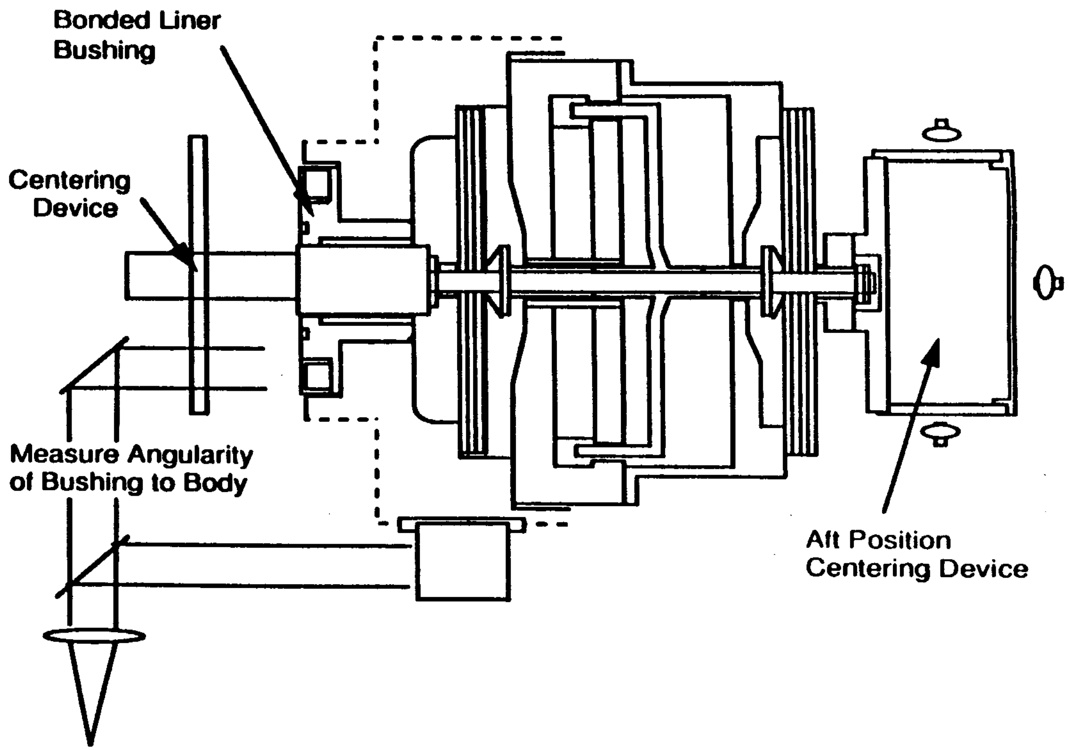
- Drilling and pinning is a "dirty" operation. Protection of hardware required during conduct of the operation.

FINAL ASSEMBLY:

- Install Liner Bushing onto body.
- Install Centering Device to Liner Bushing and Piston.
- Using Centering Device, Aft Position Centering Device and Autocollimator, both centering and angularity shall be adjusted until requirements are met.
- Adjust by moving bushing and aft spring pack.
- Tighten bushing and (9/12) aft spring pack outer bolt circle.
- Final drill aft spring pack holes and install tight tolerance pins (3/12) in aft spring pack.
- Compressor -to- Compressor Alignment Maintained by Mechanical Tolerancing of Bodies.

TOP-LEVEL REQUIREMENT:

- Angularity Piston-to-Liner: <50-µrad
- Centering: <25% of Nominal Gap.



CRITICAL TECHNOLOGY DEMONSTRATIONS

CRITICAL COMPONENTS ASSESSMENT AND RESOLUTION

NO.	ITEM	RISK	RESOLUTION	COMMENTS
1	displacer thermodynamic performance	cooling capacity below specifications,	early build and test of displacer. early validation with time for rework	phase 2 testing performed for cooling capability and temperature, use laboratory and commercial compressor
2	regenerator thermal performance	cooling below specification	thermal loss and pressure drop tests on several candidates	phase 2 testing to be performed on NIST apparatus on several regenerators.
3	regenerator life capability	shifting, clumping, pulverizing etc. will change performance over lifetime	avoid use of unsupported configurations such as spheres	requires life testing on cryocooler
4	displacer clearance gap control	wear (if gaps too small or dynamics problem) or large thermal losses (if gaps too large)	validate design, manufacture and assembly on structural model	build and test displacer structural model (with regenerator ballasted) early in phase 2.
5	induced vibration	large forces resulting from large moving massses	analysis supported by scaling from existing units	displacer vibration output measured in phase 2, compressor in phase 3
6	scaling of flexure supports for larger masses	minimal risk, detailed analysis performed	additional modeling in phase 2, build and test springs	phase 2 testing. Flexures sent to PHILLIPS for evaluation
7	MTI compressor, life limiting elements	long term stability of diaphragm and plunger sensors, compressor/control instabilities, higher order vibration harmonics	system tests	In house life testing on system at MTI. Performance testing under AFPL contract.
8	internal outgassing of organics	freezing of condensibles, reduced thermal performance	modeling utilizing existing codes, design of coil/potting for fast bakeout	calculation of outgassing rates in phase 2
9	management of waste heat	high temperatures degrade thermal performance.	modeling utilizing existing codes. Verify of displacer test.	critical for flexure compressor demonstrate manufacturing during phase2

PHASE 2 PRINCIPAL TEST ACTIVITIES

BUILD AND TEST A STRUCTURAL MODEL OF DISPLACER TO DEMONSTRATE ALIGNMENT, DYNAMICS AND MANUFACTURING

BUILD AND TEST A THERMAL DISPLACER TEST BED TO VERIFY ADEQUATE COOLING AND OPTIMIZE PARAMETERS

THE ABOVE UNITS WOULD UTILIZE AN EXISTING COMPRESSOR MOTOR/HOUSING AS THE DISPLACER DRIVE

LMSC WOULD BUILD A BRASSBOARD FLEXURE COMPRESSOR ON COMPANY FUNDING FOR DISPLACER TESTS

additional testing would include regenerator testing (at NIST), large flexures, low outgassing coils, and displacer induced vibration

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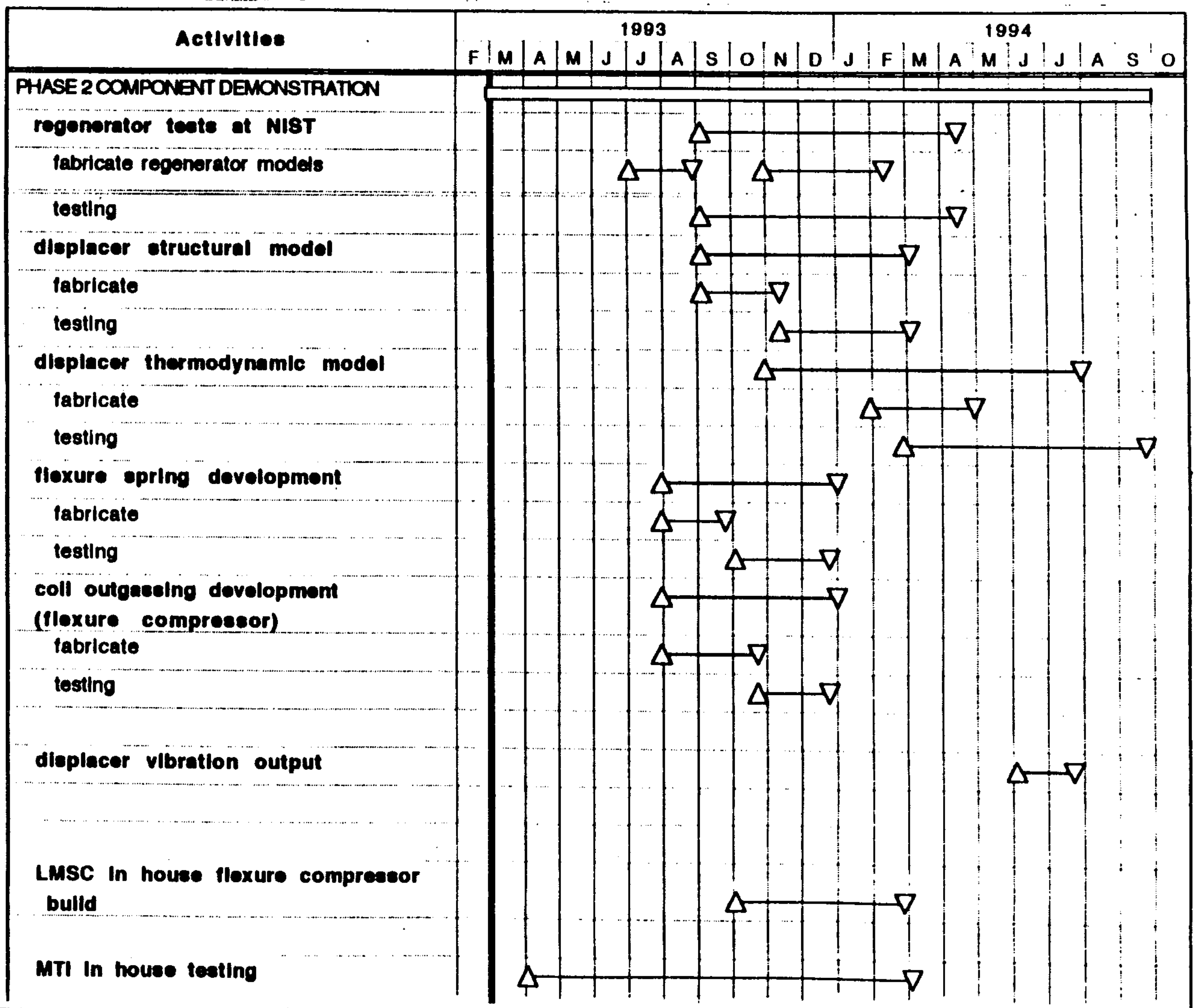
PHASE 2 CRITICAL COMPONENTS DEMONSTRATIONS

Air Force
Phillips Laboratories
10K CoDR



SUMMARY

- LOW RISK APPROACH, BASED ON AN EXTENSION OF PRESENT TECHNOLOGY
- PRESENT TECHNOLOGIES INCLUDE:
  - Electronic controller to minimize induced vibration, and provide cold tip temperature stability. Flight version to be delivered in May, 1993
  - Extensive dynamic and stress modeling of moving mass and flexures. Validation of radial motions by experimental measurements.
  - Extensive alignment work in progress by optical means, fiber optics and eddy current sensors.
  - Demonstration and measurement of low induced vibration, on similar systems.
  - Extensive development of finite element thermodynamic programs.

- SYSTEM SUBSTANTIALLY BELOW WEIGHT AND POWER LIMITS
- MTI OIL LUBRICATED COMPRESSOR SELECTED AS BASELINE
- LMSC FLEXURE BEARING COMPRESSOR CARRIED AS BACK UP PENDING DEMONSTRATION AND LIFE TESTS OF MTI COMPRESSOR
- TWO SEPARATE ANALYSES OF COOLING AND POWER CONDUCTED WITH RELATIVELY GOOD AGREEMENT. SHOW REQMTS. CAN BE EXCEEDED.
- DISPLACER DESIGN UTILIZES EXISTING SINGLE STAGE COMPRESSOR MOTOR AND CASE. PROVIDES EXCELLENT MATCH WITH SUBSTANTIAL COST AND SCHEDULE SAVINGS.
- DISPLACER DYNAMICS STUDIED AND FOUND WELL SUITED TO COMPRESSOR SPRINGS.

DISTRIBUTION LIST

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